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On the Theory of the Electric Resistance of Metals

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INTRODUCTION

THE concept of electric resistance is widely used, but the modern theory of the phenomenon is known only to theoretical physicists and specialists in the field. This is mainly due to the fact that the resistance of metals is a typical quantum phenomenon in which the wave nature of the electron plays an essential role. But it is also true that hitherto the theory has been presented in a manner suitable only for theoretical physicists who are very familiar with the formalism. It therefore seemed worth while to publish an interpretation of the fundamental ideas that is as elementary as possible without sacrificing the essential points. We begin with a qualitative account of the theory.

A metal contains a great many electrons which are detached from the atoms and move freely within the metal. The number per unit volume of these so-called *conduction electrons* varies from metal to metal, but in monovalent metals it is about equal to the number of atoms. Each atom has contributed one or more electrons to the conduction electrons, and thus has become a positive ion.

If a constant electric field is applied from outside by connecting the piece of metal to the poles of a battery, the electrons are accelerated in the direction of the force, which is opposite to that of the field because of the negative charge of the electron. If the electrons were really free within the metal, just as they are in free space, the effect of the field would be a continuous acceleration which would manifest itself as an increasing current. Actually, however, we observe a constant current for a given potential difference because the acceleration is interrupted by the interatomic electric fields which act as obstacles to the electrons. The length of the mean free path of uninterrupted flight is about 5×10^{-6} cm in silver at room temperature and increases steadily if the temperature is lowered.

Small as this length is, it is still much larger than one might expect. The conduction electrons move through very strong electric fields which surround each ion, and we should expect the path of the electron to be bent over strongly at almost every ion which it encounters. Thus the length of the mean free path should be of the order of the distance between atoms, which is about 1.5×10^{-8} cm, and not a hundred times as large as this distance, as it is found to be. Neither is there any reason to expect this distance to increase if the temperature is lowered, since the distances between atoms actually decrease on account of the thermal contraction.

There are two essential points that must be explained in the theory of electric conduction: (i) Why do the electrons move through the strong electric fields of the ions with great ease, as if they were nearly free? (ii) What are the

limits of this free motion which give rise to the resistance of the metals?

These questions can be answered completely only by considering the wave nature of the electrons. The reason that electrons can pass unimpeded through the ionic fields is found in the regular structure of the crystal lattice of the atoms in metals. The force that acts upon the electron is periodic in space, that is, it repeats itself exactly all over the crystal. If the electrons were particles in the unrestricted sense, as was assumed before the advent of wave mechanics, regularly arranged forces could not have less effect than irregularly arranged ones. The wave nature of the electron has, however, a decisive effect upon its penetration through a lattice structure, since waves react differently upon regular obstacles.

We know from optics that light waves penetrate a medium with lattice structure, such as a crystal, almost without scattering. To understand the significance of this phenomenon, we must remember that a beam of light would be strongly scattered by any single isolated atom, but the regular arrangement of the atoms in the crystal has the effect that the scattered waves interfere with and annihilate one another. The result is an unscattered beam, although the wave-length of the light is somewhat different from that of the incident beam. This is the effect known as *refraction*. Every deviation from regularity of the lattice, however, destroys the balance, and the scattered radiation no longer completely annihilates itself. Thus scattering results from cracks or inclusions of foreign matter in the crystal, or even from the irregularity produced by thermal motion of the atoms in the lattice.

Arguments of the same type hold for electron waves in a metal. If the lattice of the metal is perfect and if the temperature is so low that there are no appreciable thermal vibrations, the electron waves pass through the metal unscattered, just as light passes through a perfect crystal; that is, the ideal lattice shows no resistance to an electron wave. The electrons move within a perfect crystal just as they do in free space, except for an effect that corresponds to the refraction of light. There is a different relation for the two mediums between wave-length and frequency which means, according to wave mechanics, a different relation from the usual one between momentum and energy. A metal with ideal crystal structure would therefore have no resistance. The electric resistance of an actual metal at room temperature arises mainly from the deviation from the regular lattice due to the irregular thermal motion of the atoms. The resistance therefore increases with temperature. At very low temperatures the thermal motion becomes small and, consequently, the conductivity of the metal becomes very large. Other irregularities, such as small numbers of foreign atoms, lattice defects and cracks, are responsible for the small residual resistance that exists even at the lowest attainable temperatures.

Before elaborating a more quantitative treatment of this picture we must discuss the velocity distribution of the electrons within the metal. In spite of the fact that the electrons move nearly freely, the energy distribution is very different from the Maxwell distribution of the molecules of a gas. In the Maxwell distribution the average energy of the particles is equal to $\frac{3}{2}kT$, where k is the well-known Boltzmann constant and T is the absolute temperature. The deviation of the electron energy distribution from the Maxwell distribution is in accordance with the Pauli principle, which postulates that not more than one electron may be found in the same quantum state. It happens that, if T is room temperature, the number of quantum states with energies of the order kT is much smaller than the number of conduction electrons, and thus most of the electrons must occupy states with higher energies. The average energy is actually of the order of several electron volts, whereas kT at room temperature is about 1/40 ev. The energy distribution is shown in Fig. 1.

The Pauli principle can also be expressed in a different, more qualitative, form that sometimes allows greater insight into the phenomenon. This formulation states that two electrons cannot come much closer to each other than a distance of about λ, where λ is the wave-length which corresponds to their relative momentum p according to the de Broglie relation, $\lambda = h/p$. Let us assume that a number gN of conduction electrons are crowded within a metal, where N

is the number of atoms and g is the number of conduction electrons per atom. The average distance between electrons is $a/g^{1/3}$, where a is the interatomic distance. According to the foregoing formulation of the Pauli principle, the average electron momentum must be of the order $hg^{1/3}/a$ and their average energy $E[=p^2/2m]$ must be of the order $h^2g^{2/3}/2ma^2$. Actually, the average energy is

$$\frac{3}{5}\left(\frac{3g}{8\pi}\right)^{2/3}\frac{h^2}{2ma^2},$$

and the maximum energy corresponding to the peak of the distribution curve in Fig. 1 is

$$E_0=(3g/8\pi)^{2/3}(h^2/2ma^2)=0.23g^{2/3}(h^2/2ma^2). \quad (1)$$

This value is generally called the *Fermi energy*. The corresponding wave-length $\lambda_{\max}$ and wave number $\sigma_{\max}[=1/\lambda_{\max}]$ are:

$$\lambda_{\max}=(8\pi/3g)^{1/3}a,$$

$$\sigma_{\max}=\left(\frac{3g}{8\pi}\right)^{1/3}\frac{1}{a}=\frac{0.48}{a}g^{1/3}. \quad (2)$$

QUANTITATIVE TREATMENT

We now proceed with the quantitative calculation of the resistance. We compute the conductivity κ, which is the reciprocal value of the resistivity and may be defined as the constant of proportionality between the current density $\mathbf{i}$ and the electric field strength $\mathbf{E}$; that is,

$$\mathbf{i}=\kappa\mathbf{E}.$$

Let us attempt to express the current density $\mathbf{i}$ in terms of the acceleration of the electrons. If $\mathbf{E}=0$, the velocities of the conduction electrons are oriented at random and there is no net current. If the field $\mathbf{E}$ is established, each electron is accelerated in the direction of the field. This acceleration increases the component of the electron velocity in the direction of the field until the electron loses its acquired additional velocity and again moves at random relative to the other electrons. Let us call τ the time between two scattering processes. The velocity component $\mathbf{w}$ in the direction of the field is on the average zero just after scattering, and acquires the value,

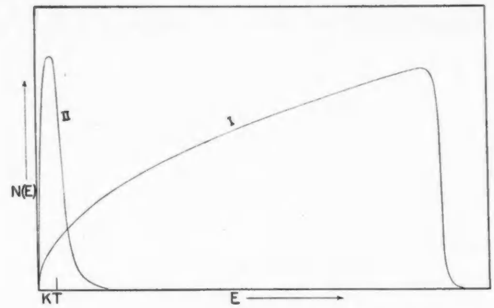

FIG. 1. Energy distribution of electrons in a metal. In curve I, $N(E)$, the number of electrons per unit energy, is plotted as function of the energy E. Curve II shows a Maxwell distribution of the same total number of electrons reduced by a factor 1/10.

$$\mathbf{w}=(e\mathbf{E}/m)\tau,$$

in the time τ. The total current density is then

$$\mathbf{i}=gNe\mathbf{w}=gNe^2\bar{\tau}\mathbf{E}/m,$$

and therefore $\kappa=gNe^2\bar{\tau}/m$, where $\bar{\tau}$ is the average of τ over all electrons.

The value of τ can be expressed in terms of the effective cross-sectional area Q of an ion for the scattering of an electron. According to well-known gas kinetic relations, the time τ is given by l/v, where l is the mean free path and v the velocity of the electron; l, in turn, is given by $1/NQ$, where N is the number of scattering obstacles per unit volume—they are the ions in our case—and Q is their cross section. Thus

$$\tau=1/NvQ, \quad (3)$$

and hence the expression for the conductivity becomes

$$\kappa=\frac{ge^2}{m\bar{v}\bar{Q}}, \quad (3a)$$

where $\bar{v}$ and $\bar{Q}$ are suitable average values of v and Q over all electrons.

A more detailed consideration[1] shows, however, that the fastest electrons only contribute significantly to the expression for κ. In order to understand this point we consider the effect of the electric field upon the electron

[1] The considerations in small print are not essential for the understanding of the remainder and can be omitted at first reading.

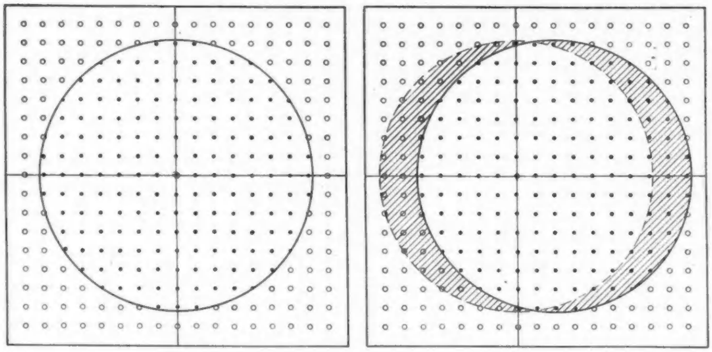

FIG. 2(*a*). (Left) The electron states of a metal represented in a diagram in the momentum-space. Every point corresponds to an electron state. Its momentum is given by the vector starting at the center and ending at the point. The states occupied by electrons are found within a sphere whose radius corresponds to the maximum momentum and are marked by solid points. The unoccupied states are marked with circles. (*b*). (Right) The electron distribution in the presence of a field. The accelerating effect of the field has removed the electrons from the shaded region at the left of the sphere to the shaded region at the right of it.

energy distribution shown in Fig. 1. In this distribution the electrons occupy states having all possible energies up to a certain maximum value. The acceleration of the electrons in the metal due to an electric field strength E consists in a constant increase of momentum of *every* electron, in the direction of the field. This effect of the field is shown in Fig. 2. The coordinate points in Fig. 2(*a*) determine the momentums of the electrons; that is, the distance from the center to a point represents in magnitude and direction the momentum of the corresponding electron. The points thus fill up a sphere whose radius is equal to the maximum electron momentum. In the absence of an electric field the center of the sphere is located at the origin of coordinates, since the average momentum is zero. If a field is present, the momentums increase uniformly in time in the direction of the force, which increase corresponds to a uniform shift of the sphere in this direction [Fig. 2(*b*)]. This shift would go on indefinitely if the electrons were completely free and unhindered in their motion; the momentums of all electrons would tend to infinity. Actually, however, the electrons are scattered on the average after a time interval τ, and the increase of momentum is then interrupted. The shift of the sphere of Fig. 2 in an electric field is therefore limited by the momentum increase that can be obtained from the field in the time τ.

We will now show that this time τ is entirely defined by the scattering of the fastest electrons only. The electrons whose momentum vectors end well within the sphere cannot be scattered at all because all states of equal or nearly equal energy are occupied, whatever may be the direction of the momentums. Only the electrons with nearly the maximum momentum can be scattered, because the movement of the sphere, upon application of the field, has emptied states of nearly maximum energy at the side of the sphere opposite to the direction of the shift. It is thus exclusively the scattering of these electrons that determines the shift of the sphere in the momentum space, since the effect of that scattering is to remove the points in front of the sphere and to add them at the rear where empty states of equal energy can be found. Consequently, it is the time interval between two scattering processes of the fastest electrons that determines the current in Eq. (1).

The next step is the calculation of the effective cross section Q of an ion for the scattering of an electron. We introduce first a few symbols connected with the calculation of wave properties. A plane wave ψ can be characterized by its wave vector $\boldsymbol{\sigma}$, whose magnitude σ is $1/\lambda$ and whose direction is that of the propagation of the wave. The value of ψ at the point (x, y, z) is given by

$$\psi(x, y, z) = A \exp(2\pi i \boldsymbol{\sigma} \cdot \mathbf{r}),$$

where $\mathbf{r}$ is the position vector of the point (x, y, z), and A is the amplitude. If ψ is an electron wave, the wave vector is related to the momentum $\mathbf{p}$ of the electron by the equation $\mathbf{p} = h\boldsymbol{\sigma}$ and to its energy $E = h^2\sigma^2/2m$. The latter equation provides the relation between the frequency and the wave-length, since the frequency ν is given by the energy relation, $E = h\nu$. If the wave is moving in a refracting medium, the relation between the wave vector and the electron energy is different,

and we may write $E=\alpha h^2\sigma^2/2m$, where α is a constant that depends on the medium. This new relation can also be expressed by stating that the mass m of the electron is changed to an *effective* mass, $m^*=m/\alpha$.

We now derive the expression for the scattering of this electron wave by an imperfection in the crystal lattice. Since the exact form of the field of the ion in the lattice is not known, we do not attempt to calculate the scattering exactly but will express it in terms of the scattering effect of a single isolated ion which is taken out of the lattice. Let us therefore first consider a single, completely isolated ion whose position vector is $\mathbf{r}_0$, and let an incident wave $\psi_i=A\exp(2\pi i\boldsymbol{\sigma}\cdot\mathbf{r})$ with a wave vector $\boldsymbol{\sigma}$ be scattered by the ion. The scattered wave expands in all directions from the ion as center. We pick up the scattered wave ψ_s in the direction $\boldsymbol{\sigma}'$ at a point whose position vector is $\mathbf{r}$, very far away from the point $\mathbf{r}_0$; the point $\mathbf{r}$ should be so far from $\mathbf{r}_0$ that, in the neighborhood of $\mathbf{r}$, the scattered wave can be considered as a plane wave in the direction $\boldsymbol{\sigma}'$. Then the scattered wave is given by

$$\psi_s=B\exp[2\pi i\boldsymbol{\sigma}'\cdot(\mathbf{r}-\mathbf{r}_0)].$$

The appearance of the difference $\mathbf{r}-\mathbf{r}_0$ in the exponent is understandable, since the phase of the wave evidently depends on the distance between the scatterer at $\mathbf{r}_0$ and the point of observation $\mathbf{r}$. The amplitude B is proportional to the strength of the incident wave at the point $\mathbf{r}_0$; that is, $B=B_0\psi_i(\mathbf{r}_0)$. Thus we obtain

$$\psi_s=B_0A\exp[2\pi i(\boldsymbol{\sigma}-\boldsymbol{\sigma}')\cdot\mathbf{r}_0]\cdot\exp[2\pi i\boldsymbol{\sigma}'\cdot\mathbf{r}]. \quad (4)$$

We do not evaluate the amplitude B_0, but we compare it with that of the wave which would be scattered by the same ion if the latter were back in the lattice but displaced from its regular position. Let the regular position be given by $\mathbf{r}_0$ and the displaced position by $\mathbf{r}_0+\mathbf{d}$. The displacement $\mathbf{d}$ should be small compared to the wave-length. As long as the ions are undisplaced, all scattered waves interfere with one another and the result is an unscattered but refracted beam. The displacement of the ion removes the center of the scattered wave from its regular position. The effect of the displacement can be divided into two parts: (i) the effect of the removal of the wave scattered at the original position, and (ii) the effect of the scattering at the displaced position. Since before displacement all scattered waves have annihilated one another by interference, the effect of the removal of one scattered wave is *zero minus the removed wave*, and this is identical with the originally scattered wave taken with opposite amplitude. The effect (ii) is just a scattered wave like the original one whose origin is at the displaced position. We therefore get all together a wave that is the superposition of a scattered wave at the displaced position $\mathbf{r}_0+\mathbf{d}$ and the negative of the scattered wave at the original position, or

$$\psi_d=\psi_s^{\mathbf{r}_0+\mathbf{d}}-\psi_s^{\mathbf{r}_0}.$$

Here the subscripts $_d$ and $_s$ refer, respectively, to the scattering due to displacement and the scattering due to a single ion. The superscripts $^{\mathbf{r}_0+\mathbf{d}}$ and $^{\mathbf{r}_0}$ signify the origin of the scattered waves. Since $\mathbf{d}$ is small, we may expand the expression in a Maclaurin series and obtain

$$\psi_d=\mathbf{d}\cdot\mathrm{grad}_{r_0}\psi_s,$$

where $\mathrm{grad}_{r_0}\psi_s$ signifies the vector given by the differentiations of ψ_s with respect to the coordinates of $\mathbf{r}_0$. By virtue of Eq. (4) we get

$$\psi_d=2\pi i[(\boldsymbol{\sigma}-\boldsymbol{\sigma}')\cdot\mathbf{d}]\psi_s. \quad (5)$$

The scattering by the displaced ion differs from the scattering by the isolated ion by the factor $2\pi(\boldsymbol{\sigma}-\boldsymbol{\sigma}')\cdot\mathbf{d}$ in the amplitude.[2]

We now express this result in terms of scattering cross sections. Let Q_s be the effective cross section of a separated ion for the scattering of an electron; then the cross section Q_d for scattering by a displacement d is

$$Q_d=4\pi^2[(\boldsymbol{\sigma}-\boldsymbol{\sigma}')\cdot\mathbf{d}]^2Q_s,$$

[2] The present treatment is only approximately correct. The approximation is mainly contained in the statement that the wave within the metal is purely sinusoidal. Actually—in optics as well as here—a wave in the periodic medium is given by $\psi=A\exp(2\pi i\boldsymbol{\sigma}\cdot\mathbf{r})u(x,y,z)$, where u is a function with the same periodicity as the lattice. The wave is *modulated* periodically by the lattice. It is therefore not exactly correct to say that $\mathrm{grad}\,\psi=2\pi i\boldsymbol{\sigma}\psi$, as is done in the text. It is actually $[2\pi i\boldsymbol{\sigma}+(\mathrm{grad}\,u)/u]\psi$. In the case of almost free electrons in the lattice the modulation is weak and our approximation is good. But even for strong modulation our approximation gives the right order of magnitude.

since the ratio of the cross sections Q_d and Q_s must be equal to the ratio of the intensities of the scattered waves. The intensities, in turn, are proportional to the squares of the amplitudes whose ratio is given by Eq. (5). The factor $[(\boldsymbol{\sigma}-\boldsymbol{\sigma}')\cdot\mathbf{d}]^2$, as well as Q_s, depends on the direction of the incident wave, whose wave vector is $\boldsymbol{\sigma}$ relative to that of the scattered wave whose vector is σ'. We take the average of Q_d over all different directions of the displacement **d**—which, of course, are equally probable—and obtain

$$\bar{Q}_d=(4\pi^2/3)\,|\boldsymbol{\sigma}-\boldsymbol{\sigma}'|^2 d^2 Q_s,$$

since the average of the squares of the cosines of the angles between $\boldsymbol{\sigma}-\boldsymbol{\sigma}'$ and **d** is $\frac{1}{3}$. The energy loss of the electron in the scattering process is very small since the ions are much more massive than the electron; hence, $|\boldsymbol{\sigma}|$ is approximately equal to $|\boldsymbol{\sigma}'|$, which means that the scattered and the incident waves differ only in direction. We then find that $|\boldsymbol{\sigma}-\boldsymbol{\sigma}'|=2|\boldsymbol{\sigma}|\sin\frac{1}{2}\alpha$, where α is the scattering angle, that is, the angle between $\boldsymbol{\sigma}$ and $\boldsymbol{\sigma}'$. Hence

$$\bar{Q}_d=(4\pi^2/3)\sigma^2 d^2\cdot 4\sin^2\tfrac{1}{2}\alpha Q_s. \tag{6}$$

Since the value of Q_s and its dependence upon angle are not well known, we may introduce a mean value $\bar{Q}_s$, which is the average of $2\sin^2\frac{1}{2}\alpha Q_s$, and obtain

$$\bar{Q}_d=(8\pi^2/3)\sigma^2 d^2\bar{Q}_s.$$

This is the cross section that occurs in Eq. (3a) for the conductivity. We thus obtain

$$\kappa=(3/8\pi^2)(ge^2/mv\sigma^2 d^2\bar{Q}_s), \tag{7}$$

where v and σ are the velocity and wave number of the fastest electrons in the metal, in accordance with the paragraphs in small print following Eq. (3a).

It remains to calculate the value of the displacement d. We consider here only the displacements due to the thermal vibrations. To simplify the description of the thermal motion of the atoms in the lattice we will use the so-called *Einstein model*, in which each atom is regarded as an independent oscillator capable of vibrating in any direction with a frequency ν. This frequency is connected with the so-called *Debye temperature* Θ of the metal by means of the relation,

$$h\nu=k\Theta.$$

Since every atom is pictured as an oscillator having three vibratory degrees of freedom, its average energy E at the temperature T is $3kT$. The energy E of an oscillator and the mean-square displacement $\bar{d}^2$ are related by the equation,

$$\bar{d}^2=E/4\pi^2M\nu^2=3kT/4\pi^2M\nu^2$$
$$=3Th^2/4\pi^2Mk\Theta^2, \tag{8}$$

in which M is the mass of the atom. We therefore get our final expression for the conductivity from Eq. (7):

$$\kappa=\frac{1}{2}\frac{ge^2}{m}\frac{1}{vp^2\bar{Q}_s}\frac{Mk\Theta^2}{T}. \tag{9}$$

Here $h\boldsymbol{\sigma}$ has been replaced by the electron momentum **p**, and the quantities v and p refer to the fastest electrons in the metal. The conductivity is now expressed in terms of quantities that are known, with the exception of the cross section $\bar{Q}_s$ of a single ion. Even the more elaborate derivations cannot get much further than this, since little is known about the exact structure of ions in metals. However, we shall get the right order of magnitude by putting $\bar{Q}_s\sim a^2$; that is, the cross section for scattering by a single ion is of the order of the square of the lattice distance a. The latter distance is about equal to the diameter of an ion, and this will be the essential magnitude for the determination of $\bar{Q}_s$. Actually $\bar{Q}_s$ is somewhat smaller than a^2 because of the fact that a good part of the scattering field of the ion is shielded by the negative charge of the conduction electrons. This shielding effect is greater for smaller lattice distances, since smaller distances between atoms allow the conduction electrons to spread more uniformly over the metal and thus to cover up the ions more efficiently. We may therefore assume that

$$\bar{Q}_s=f(a)a^2, \tag{10}$$

where $f(a)$ is somewhat smaller than unity and increases slightly as a increases.

Equation (9) shows clearly the well-known dependence of the conductivity on the temperature. This dependence can easily be traced back to the fact that the square of the amplitude of the lattice oscillations is proportional to T and, therefore, so is the effect of these vibrations on the resistance.

In order to obtain an estimate of the value of κ, let us consider silver, for which g is 1 and Θ is 223°K. Using $p=h/\lambda$, we write Eq. (9) in the form,

$$\kappa=\frac{e^2}{h\lambda}\left(\frac{g}{2}\frac{\lambda^2}{\bar{Q}_s}\frac{M}{m}\frac{k\Theta}{v\cdot p}\frac{\Theta}{T}\right).$$

Each fraction in the parenthesis is a pure number. For silver, M/m equals 195,000; kT is an energy whose value is 0.019 ev; vp is twice the kinetic energy of an electron and, according to Eq. (1), is equal to $0.23h^2/ma^2$. The lattice distance a in silver is 1.44×10^{-8} cm, so that vp is 7.7 ev. We assume that $\bar{Q}_s=a^2$ and get, according to Eq. (2), $\lambda^2/\bar{Q}_s=(8\pi/3)^{\frac{2}{3}}$. All together we obtain approximately, assuming $T=273$°K,

$$\kappa=4.3\ e^2/h\lambda=0.22\times10^{18}\ \text{sec}^{-1}.$$

This is equal to 0.25×10^6 ohm^{-1} cm^{-1}. The actual value is 0.66×10^6 ohm^{-1} cm^{-1}, which is close enough in view of our rough assumptions concerning $\bar{Q}_s$. In this case the value of $f(a)$ introduced in Eq. (10) would be about 0.38.

Table I gives a list of monovalent metals, for which we may put g equal to unity. It contains the lattice distances a, the masses M of the atoms and the Debye temperatures Θ. The observed value of κ at 0°C is given and also a "reduced" value, κ_0, related to κ by the equation,

$$\kappa_0=\kappa\frac{T}{M\Theta^2}=\frac{ge^2}{2m}\frac{k}{vh^2\sigma^2\bar{Q}_s}.$$

In this reduced value the effects of the elastic lattice properties on the conductivity are eliminated. As the table shows, the values of κ_0 vary much less than the values of κ. If we substitute in this expression for κ_0 the value of $\bar{Q}_s$ from Eq. (6), we obtain

$$\kappa_0=\frac{ge^2}{2m}\frac{k}{f(a)v\sigma^2h^2a^2},$$

and it is easily seen why κ_0 should be essentially the same for all monovalent metals. The product σ^2a^2 is constant [see Eq. (2)], $f(a)$ is an increasing function of a and $v[\sim\sigma]$ is a decreasing function of a. There are, of course, individual fluctuations of the value of κ_0. In the case of sodium, for example, κ_0 is very large, which points to a very small value for $\bar{Q}_s$. The sodium ions are unusually well shielded by the conduction electrons.

THE BAND STRUCTURE OF THE ELECTRON SPECTRUM

The statement made in the introduction that electron waves penetrate perfect periodic lattices without perturbation must be qualified. We apply again the optical analogy. It is known that light of very short wave-length (x-rays) cannot penetrate crystals and is totally reflected, if the wave-length and direction of the light fulfil the Bragg relation, namely, $n\lambda=2b\sin\varphi$, where b is the distance between two adjacent parallel planes of atoms in the crystal, φ is the angle of incidence of the beam relative to the planes and n is an integer. Every set of parallel planes of atoms has a definite distance b which, in a simple cubic lattice, is equal to or less than

TABLE I. Characteristic values for various metals.

Metal	a (10^{-8} cm)	M (mass units)	Θ	κ at 0°C (10^6 ohm^{-1} cm^{-1})	κ_0
		(a) Monovalent metals			
Li	1.52	6.9	363	11.8	35.3
Na	1.86	23.0	202	23	65.5
K	2.31	39.1	163	15.9	42
Cu	1.28	63.57	333	64.5	25.0
Rb	2.43	85.44	85	8.6	38.2
Ag	1.44	107.9	223	66.7	33.9
Cs	2.62	132.9	54	5.6	38.6
Au	1.44	197.2	175	49	22.2
		(b) Divalent metals			
Be	1.12	9.02	1000	18	5.5
Mg	1.60	24.3	357	25	22.2
Ca	1.96	40.1	230	23.5	30.2
Zn	1.33	65.4	213	18.1	16.7
Sr	2.15	87.6	171	3.3	3.6
Cd	1.49	112.4	172	15	12.3
Ba	2.17	137.4	113	1.7	2.7
		(c) Some transition metals			
Fe	1.24	55.8	420	11.2	3.1
Co	1.25	58.9	401	16	4.65
Ni	1.24	58.7	375	16	5.2
Os	1.35	191.5	256	11	2.46
Ir	1.35	193.1	316	20	2.73
Pt	1.38	195.2	240	10.2	2.48

the lattice distance a. The Bragg relation can also be expressed in terms of the wave vector $\boldsymbol{\sigma}$ instead of the wave-length; thus,

$$\sigma \sin \varphi = n/2b. \quad n=1, 2, \cdots. \tag{11}$$

These relations are represented in Fig. 3 in the following manner. If the wave vector $\boldsymbol{\sigma}$ is plotted from the origin of Fig. 3 and if its end lies on one of the straight heavy lines, then it fulfils one of Eqs. (11). Each heavy line corresponds to a set of parallel planes of atoms; the direction of the line is parallel to the corresponding planes and its distance from the origin is equal to $n/2b$. The lines closest to the origin of Fig. 3 are those that correspond to $n=1$ and the largest possible value of b, namely, $b=a$. Their distance from the center thus is $1/2a$. Wave vectors shorter than $1/2a$ never fulfil the Bragg relation.

When these ideas are applied to electron waves in metals, we come to the conclusion that electrons whose wave vectors fulfil Eqs. (11) cannot penetrate a crystal. The statement that a perfect crystal offers no impediment to electron waves must be qualified to the extent that it is true only if $\boldsymbol{\sigma}$ does not fulfil the Bragg relation. There are, therefore, waves of certain wave-lengths and directions that are forbidden within a crystal.

The Bragg relation is of no importance for monovalent metals since the wave vectors occurring there are small enough so that Eqs. (11) can never be fulfilled. The minimum value of σ for which Eqs. (11) may be valid is $1/2a$. The maximum value of σ in monovalent metals ($g=1$) is, according to Eq. (1),

$$\sigma_{\max} = \left(\frac{3}{8\pi}\right)^{\frac{1}{3}} \frac{1}{a} < \frac{1}{2a}.$$

If g, the number of electrons per atom, is larger than one, as is the case for divalent metals, the Bragg relation may, however, be fulfilled for some of the electrons.

The Bragg relation asserts that, in a given direction, one particular value of the wave-length, or of the wave number σ, is forbidden inside the crystal. The resulting gap, if measured in wave numbers, is therefore infinitely thin. This corresponds, however, to a finite gap in energy, because of a characteristic feature of the

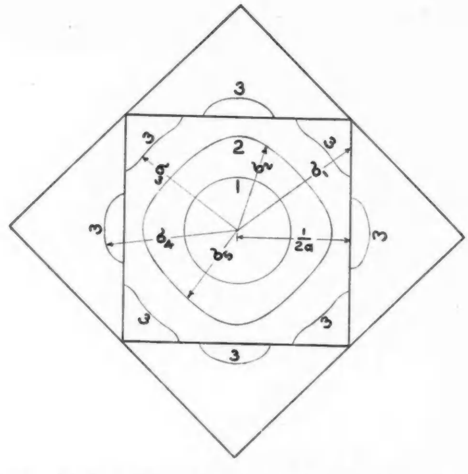

FIG. 3. Representation of the Bragg relation for a simple cubic lattice in the momentum space. A wave vector $\boldsymbol{\sigma}$ which, if plotted from the origin, reaches one of the heavy lines fulfils the Bragg relation and is forbidden. Thus $\boldsymbol{\sigma}_1$ is a forbidden vector. The light lines *1*, *2*, and *3* connect end points of vectors that represent states of equal energy; for example, the pair of wave vectors $\boldsymbol{\sigma}_2, \boldsymbol{\sigma}_5$ corresponds to one energy, the pair $\boldsymbol{\sigma}_3, \boldsymbol{\sigma}_4$ to another.

energy-wave number relation, namely, that the energy value is depressed for wave numbers below the forbidden one and raised for those above the forbidden one if compared to the value of the free electron, as shown in Fig. 4. (The same effect is responsible for the deviation in Fig. 3 of the lines of equal energy from a circular shape, when they are near the lines that represent the Bragg relation.) Thus the allowed energy values for an electron in a crystal constitute a spectrum that consists of continuous bands interrupted by gaps of forbidden energies. The gaps are impervious to an electron accelerated by an electrostatic field for, if the electron acquires the energy (or frequency) corresponding to a gap, the electron wave fulfils the Bragg relation and is reflected, and its direction is reversed, so that it runs counter to the field and loses its energy.

It is characteristic of the divalent metals, for which g is two, that the wave-lengths of their fastest electrons are just in the region where Bragg reflections may occur; in some directions their energies lie above the gap, in some others below, but always they are rather close to it. This close proximity to the gap influences the

properties of the electron decisively. Although total reflection of the wave occurs only at the Bragg value itself, there is a strong partial reflection for wave-lengths near the gap. The electron is therefore slowed down and the effect corresponds to a larger inertia, that is, to a larger effective mass of the electron. It now can be easily understood why the conductivities of the divalent metals are much smaller than would be expected from the simple formula of Eq. (9). The mass of the electron occurs in the denominator of this expression, and hence a larger effective mass reduces the conductivity. Table I shows that the values of κ_0 for the divalent metals are considerably smaller than the corresponding values for the neighboring monovalent metals in the periodic system.

In some cases the electron distribution in a crystal is such that the electrons fill all energy states up to a certain gap so that there is no empty state below and no occupied state above the gap. In this case no current can be produced by an electrostatic field because, as we have previously seen, the electrons cannot pass over the gap under the influence of the field, and there is no possibility of acceleration of those electrons whose energies are below the gap, since all states are occupied. Such a crystal is an insulator. Electron transitions from one band to another—crossings of gaps—are possible by other means, as, for example, if energy is supplied in the form of heat or by absorption of light. The creation of conductivity by the action of light, or *photoconductivity*, is a well-known effect in most insulators. The conductivity induced by heat is negligible if the gap is larger than the average available heat energy kT.

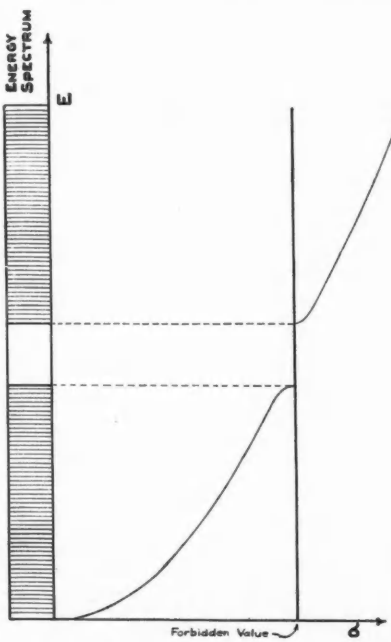

FIG. 4. The energy spectrum of electrons in a crystal lattice. The energy E is plotted as a function of the wave number σ. The resulting spectrum is indicated along the E axis.

The width of the gap corresponds in our optical analogy to the width of the frequency region of total reflection. It depends essentially upon the degree of the interaction between the waves and the lattice points. It would lead us too far afield to discuss the details of this point, but it may be added that this interaction is especially strong in ionic crystals such as rock-salt, because of the strong electric field of the ions. The energy gaps are very wide and ionic crystals are good insulators.

Another interesting group of metals is the *transition metals*. Their name comes from the position they occupy in the periodic system of elements. Their chemical and physical properties are determined by a peculiarity in the electronic structure of their atoms. The atom is surrounded by one or two loosely bound valence electrons which constitute the conduction electrons. The rest of the electronic structure consists of electron shells containing more tightly bound electrons. It is characteristic of the transition metals that these shells are not completely occupied; there are still a number of free places left. This number is three in iron, two in cobalt, one in nickel, and so forth. The conduction electrons have a tendency to jump into these free places and to stay there for some time, until they are again ejected by some small fluctuation of the field. This tendency acts as an additional cause of interrupting the acceleration by the field and increases appreciably the scattering cross section of the single ion. This is why the conductivity of the transition metals is even lower than that of the divalent metals.

SUMMARY

The most important characteristics for a good conductor are:

(1) Monovalency, in order that the energy of the electrons may be as far away as possible for any energy gap so that no strong partial reflection occurs at crystal planes.

(2) Large atomic mass, so as to decrease the amplitude of the thermal vibrations and thus the scattering effect of these vibrations.

(3) The harder the metal, the higher the frequency of the atomic vibrations and thus the smaller their amplitude for a given energy. In our equations the hardness is measured in terms of the Debye temperature; harder metals have higher Debye temperatures. In view of these conditions it is easily seen that the alkali metals, although they fulfil the first conditions, are not the best conductors because of their softness. The noble metals—silver, copper and gold—are hard and therefore good conductors. Although gold has the most massive atom of the three metals, its hardness and hence also its conductivity are inferior to those of silver and copper.

THE RESISTANCE AT LOW TEMPERATURES

The foregoing considerations, in which it was shown that the conductivity of a metal is proportional to $1/T$, lead us to expect a decrease in resistance if the temperature is lowered. This predicted decrease is observed for temperatures above the Debye temperature Θ, but below this temperature the resistance decreases far more rapidly than $1/T$. The reason for this is that our computation of the average displacement d of an atom is no longer valid. Especially the assumption of Einstein that every atom in the lattice oscillates as an independent oscillator is no longer a good approximation. We will now discuss the improvements that have to be introduced in the calculation of the displacement at low temperatures.

The lattice motions can be described as a superposition of elastic stationary waves, whose wave-lengths cover a wide range; the greatest value of λ is comparable to the dimensions of the total crystal and the least value is of the order of the interatomic distance a. The frequency ν of an elastic wave is related to the wave-length by the relation $\nu = c/\lambda$, where c is the velocity of sound in the metal. The highest frequency $\nu_{\max}$ is connected with the Debye temperature in the same way as is the Einstein frequency ν previously used; that is, $h\nu_{\max} = k\Theta$. A simple theorem[3] about stationary waves states that the number of stationary waves with frequencies below a value ν is proportional to ν^3.

The displacement d of one ion is composed of the contributions of all elastic waves according to the equation,

$$d^2 = \sum_i d_i^2,$$

where d_i is the displacement due to the ith standing wave. The squares of the contributions d_i add up, in this way, to give the square of the total displacement because the periodic displacements due to the different elastic waves are all out of phase and incoherent. Each value d_i is equal to the amplitude of an elastic stationary wave. Since the latter can be considered as equivalent to an oscillator, we may again use the relation between the energy and the square of the amplitude,

$$d_i^2 = E_i/4\pi^2\nu_i^2\mu,$$

where E_i is the energy of the elastic wave and μ is the equivalent vibrating mass, which is of the order of the mass of the full crystal but need not be determined here. If the temperature T is higher than Θ, the thermal energy is larger than any of the energy quanta $h\nu_i$ of the elastic waves. The average energy of each wave is then kT. We thus obtain

$$d^2_{T>\Theta} = \sum_i \frac{kT}{4\pi^2\mu\nu_i^2} = Z\frac{kT}{4\pi^2\mu}\frac{1}{\bar{\nu}_i^2}, \tag{12}$$

where Z is the number of elastic vibrations, and $\bar{\nu}_i$ is a suitable average. This average $\bar{\nu}_i$ is very near to the highest frequency $\nu_{\max}$ because the number of elastic waves is so much larger for higher frequencies.[4]

[3] This theorem is applied in many other fields as well. It holds for stationary light waves in a cavity with reflecting walls and is used in that connection to derive Planck's law. It also holds for the number of possible electron waves in a metal with an energy, and therefore a frequency, less than a prescribed value.

[4] This displacement was calculated previously and found to be $d^2 = kT/4\pi^2M\nu^2$. Since the total number Z of elastic vibrations is equal to $3N$, where N is the number of atoms, we find by comparison that $\mu = NM$ if we assume that $\bar{\nu}_i = \nu$.

We will now discuss the value of d^2 for $T<\Theta$. First, some of the elastic vibrations of higher frequency have energies $h\nu_i$ that are larger than kT; such vibrations cannot be excited. We may assume as a rough approximation that *only* those vibrations are excited whose frequencies ν_i are less than kT. The number of these vibrations obviously is smaller than Z; actually it is ZT^3/Θ^3, since the number of vibrations up to a certain frequency ν is proportional to ν^3 and $\nu_{\max}=k\Theta/h$, whereas the highest excited frequency ν is only kT/h. We therefore obtain for the displacement $d_{T<\Theta}$ at low temperatures,

$$\overset{2}{d}_{T<\Theta}=Z\frac{T^3}{\Theta^3}\frac{kT}{4\pi^2\mu}\frac{1}{\bar{\bar{\nu}}_i{}^2},$$

where $\bar{\bar{\nu}}_i$ is an average of the frequencies ν_i from the smallest up to kT/h; $\bar{\bar{\nu}}_i$ is about equal to the highest frequency included, namely $\nu_{\max}T/\Theta$, for the reasons previously mentioned. We then get

$$\overset{2}{d}_{T<\Theta}=Z\frac{T^3}{\Theta^3}\frac{kT}{4\pi^2\mu}\left(\frac{\Theta}{\nu_{\max}\,T}\right)^2=\overset{2}{d}_{T>\Theta}\frac{T}{\Theta},$$

or, in view of Eq. (8),

$$\overset{2}{d}_{T<\Theta}=\frac{3Th^2}{4\pi^2Mk\Theta^2}\cdot\frac{T}{\Theta}. \tag{13}$$

This expression gives the displacement d of the atom from its rest position.

There is another important difference at low temperature in the scattering of electrons due to the displacements. The latter give rise only to scattering through small angles, as can be seen in the following way. The momentum of the electron is changed in the scattering process, and this difference must appear in some other form within the metal, namely, as the momentum of an elastic wave. The magnitude of this momentum is restricted, however, because the energy transfer to this elastic wave on the average cannot be larger than kT. The momentum P of a wave of energy kT is given by kT/c, where c is the wave velocity, which is in the present case the velocity of sound. Is this momentum difference large enough to deflect the electron out of its path? The momentum of the fastest electrons is $p\sim h/a$, where a is the interatomic distance. The velocity of sound is given by $c\sim a\nu_{\max}$, since the wave-length of the highest elastic frequency is of the order of the interatomic distance. We thus get

$$P\cong\frac{kT}{a\nu_{\max}}\cong\frac{T}{\Theta}p,$$

since the Debye temperature Θ is given by $h\nu_{\max}/k$. The momentum P which can be acquired by the elastic waves is thus at least of the same order as p if $T>\Theta$, but is much smaller than p if $T\ll\Theta$. This means that at low temperatures the electron is scattered only through a small angle whose magnitude, in radians, is given by T/Θ. Two consequences result from this fact. We can see from Eq. (6) that the cross section Q_d is proportional to $\sin^2\frac{1}{2}\alpha$, where α is the scattering angle. Since this angle is now (for $T\ll\Theta$) always as small as T/Θ, we can replace the sine by the angle and obtain from Eq. (6),

$$Q_d=\frac{4\pi^2}{3}\sigma^2\overset{2}{d}_{T<\Theta}\frac{T^2}{\Theta^2}Q_s.$$

Furthermore, because of the small-angle scattering, a large number of scattering processes, namely Θ/T, are required before the electron is scattered far from its original direction. The time interval τ after which an electron is completely scattered from its original direction is therefore no longer given by Eq. (3) but by

$$\tau=\frac{\Theta}{T}\frac{1}{vNQ_d},$$

and the conductivity [see Eq. (3a)] is given by

$$\kappa=\frac{\Theta}{T}\frac{ge^2}{m}\frac{1}{vQ_d}.$$

If one now inserts Eq. (13) in Eq. (14) and this into Eq. (15), the result is our final expression,

$$\kappa=\frac{ge^2}{m}\frac{Mk\Theta^2}{v\sigma^2h^2TQ_s}\frac{\Theta^4}{T^4}\ \text{(valid if } T\ll\Theta).$$

Hence the expression for the conductivity at low temperature differs from the one at normal temperatures ($T>\Theta$) by the factor Θ^4/T^4 and

shows a very strong temperature dependence proportional to $1/T$.[5]

SURVEY OF FURTHER DEVELOPMENTS

This article is intended to present the fundamental ideas of the theory of metallic conduction in the simplest possible way. It is obvious that the developments and refinements of the theory cannot be presented with similar elementary methods. Much work has been done to determine the exact value of the cross section Q_s for electron scattering by an ion. Wigner and Seitz[5] have developed a method to determine the electron distribution around the ions when they are built into the crystal, and Bardeen[6] has investigated the details of the effect of the ion displacement on the conduction electrons. We have assumed, in our approximation, that the ion is not deformed during the displacement; actually it suffers deformation and thus changes its scattering ability.

The theory has been successful in explaining the conductivity of alloys. There are two types of alloy, one in which the atoms of the different metals are distributed at random over the lattice points, another in which the atoms of the components are regularly arranged. The conductivity of the former type is found to be small compared to its value in the pure metals, because the random distribution is an element of disorder and produces additional scattering of the electron waves. Alloys of the other type do not show the decrease in conductivity.

The transition metals have been studied widely, especially because some of them show ferromagnetic properties which are also connected with the incompletely filled electron shells that are responsible for the lower conductivity. Electric and thermal conductivity are intimately connected since the thermal energy also is mainly transported by the conduction electrons. The ratio $\kappa_{\text{thermal}}/\kappa_{\text{electric}}$ of the two conductivities is to a good approximation equal to $3k^2T/e^2$. This relation—the Wiedemann-Franz law—is moderately well fulfilled, and the deviations could be explained by the modern theory.

It can be stated that, in general, the phenomena connected with metallic conduction are well understood in terms of the modern theory whose fundamental concepts are described in this article. There are many points of detail, however, where the mathematical complications are too great to permit the calculation of quantitative results. In these cases, approximation methods must be applied and they give only qualitative answers which are all too often not very satisfactory.

One important group of phenomena has so far defied any attempted explanation, namely, *superconductivity*, which is a property of a large number of metals and which consists in an unusually large conductivity below a certain critical temperature of only a few degrees above the absolute zero. As was shown in the previous section, the conductivity increases very markedly with falling temperature. The superconducting metals, however, show a sudden jump at the critical temperature to unbelievably high values of conductivity. A current, once created, can run for weeks in a closed circuit without any electromotive force, before it dies down. No satisfactory explanation has been given for these strange phenomena.

[5] E. Wigner and F. Seitz, Phys. Rev. **43**, 804 (1933); Phys. Rev. **46**, 509 (1934).
[6] J. Bardeen, Phys. Rev. **52**, 688 (1937).

NO man has come to true greatness who has not felt in some degree that his life belongs to his race and that what God gives him He gives him for mankind.
—PHILLIPS BROOKS.

Electric Fish

R. T. Cox
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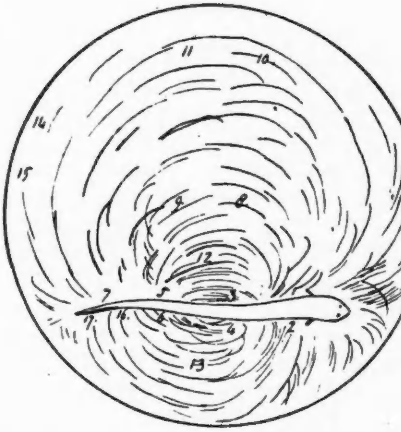
IT is now more than six years ago that Mr. Christopher Coates, the Aquarist of the New York Aquarium, sent a message to our laboratory asking for help in measuring the voltage of an electric fish. None of us knew much more about electric fish than that they existed and had been the subject of some seldom remembered researches of Cavendish and Faraday. But the question seemed a curious one, and so it happened that some while afterward we were setting up a cathode-ray oscillograph in Mr. Coates' narrow laboratory in the old Aquarium building, now abandoned. On one side were tanks of tropical fish between us and the visitors in the gallery and on the other side the heavy masonry that had been the walls of Fort Clinton and the cellars that had been gunpowder pits when the fort was a part of the defenses of New York Harbor.

The observations thus casually begun in the expectation that they would make a few days of interesting work have since absorbed much of the time of a number of collaborators, and they have taken some of us much farther afield than the old Aquarium building in Battery Park. We have improvised a laboratory partly on a fish pier at Point Lookout, Long Island, and partly on a live-well floating alongside, and we have traveled for electric fish as far as the coast of Florida and the mouth of the Amazon. Incidentally we have run across some curious bypaths in the history of electricity that extended from the accounts of electric fish in the early records of the Mediterranean region and the recorded practice of electrotherapy by the Indians of Guiana to the researches of the pioneer experimenters in "animal electricity."

No one knows just how many species of electric fish there are. They are found in a number of different genera scattered widely over the diverse waters of the world. Their shock must have been one of the very first electrical phenomena to be observed. The electric catfish of the Nile, *Malapterurus*, is pictured on the walls of early Egyptian tombs with fishermen who must have been acquainted with its electric power, whatever explanation they may have had for it. In the same pictures are shown fish of the mormyrid family, some species of which are weakly electric. In the sea water of the same part of the world is found the electric ray known to the Greeks as *narke* and to the Romans as *torpedo*. This fish is found pictured in the ruins of Pompeii, and Pliny wrote of it, with some exaggeration, that "from a considerable distance even, and if only touched with the end of a spear or staff, this fish has the property of benumbing even the most vigorous arm, and of riveting the feet of the runner, however swift he may be in the race."

It was this property of causing numbness that gave the fish its Greek and Roman names, which have the same roots as *narcotic* and *torporific*. Perhaps also it suggested the use of the shock of the fish, as described by Galen, as a cure for severe headache, which must be the earliest recorded application of electricity to any human need. The treatment of paralysis by the shock of



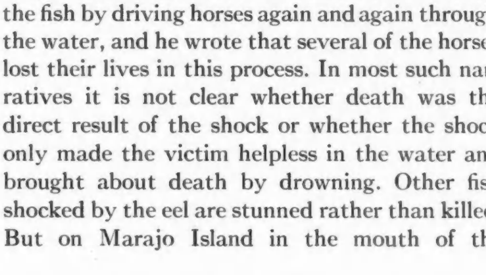
Sketch from Faraday's *Diary* showing lines of current around an electric eel. The numbers show the positions in the water of the hands of various observers. Faraday's comment: "But what an enormous quantity of electricity there must be to give such a general and universal shock."

Bas-relief from an Egyptian tomb showing fishermen with various species of fish, including two varieties of mormyrid. The species cannot be identified with certainty, but the fish in the upper center is probably of an electric species. [Courtesy of the Metropolitan Museum of Art, New York.]

the electric eel, as practiced among the Indians of Guiana, is a similar instance probably more in accord with modern medical practice.

These words which were once the names of a single variety have since been used for two different genera of electric fish. The genus *Torpedo*, besides the fish to which the name was first applied, includes also the largest of all electric fish, *Torpedo occidentalis*, found on the North Atlantic coast of the United States. The genus *Narcine* comprises an uncertain number of electric species of the ray family found in the warmer waters of both the Atlantic and Pacific Oceans. Another marine fish of the Western Hemisphere is *Astroscopus*, the star-gazer, so called because its eyes are on the top of its head and stare forever upward. It makes use of this characteristic by burying itself up to the eyes in the bottom sand and releasing its electric charge when some other fish swims over it into its field of view.

Although *Torpedo occidentalis* is the largest of the electric fish, reaching a weight of 60 kg, the most highly specialized and the most formidable is the electric eel, *Electrophorus electricus*—called *Gymnotus* in the older writings—which inhabits the rivers of the Amazon and Orinoco systems. Its danger is entirely in its electric power; like the electric species generally, it is otherwise almost defenseless. It has neither scales nor spines and only small teeth. It is a rather weak swimmer, propelling itself forward or backward, with equal facility but not much power, by a sinusoidal motion of the long fin which runs along the under side of its body. Its eyes are not well developed and in the adults are always cloudy. This cloudiness may be an injury caused by the electric discharge, as some medical evidence suggests, although the eyes of other electric species are normal. In spite of these handicaps its electric power makes it dangerous. Stories are common in South America of its causing the death of men, horses and cattle. Alexander von Humboldt has described how the Indians who caught specimens for his research, first exhausted the fish by driving horses again and again through the water, and he wrote that several of the horses lost their lives in this process. In most such narratives it is not clear whether death was the direct result of the shock or whether the shock only made the victim helpless in the water and brought about death by drowning. Other fish shocked by the eel are stunned rather than killed. But on Marajo Island in the mouth of the

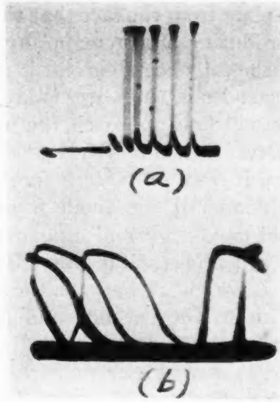


A horse shocked by an electric eel. From the title page of *Dr. Carl Sachs Untersuchungen am Zitteraal, Gymnotus electricus*, edited by Emil duBois-Reymond (Leipzig 1881). The initials, E. dB-R., on the left seem to show that the engraving was made from a drawing by du Bois-Reymond.

Amazon an old ranch hand told us how he was once riding a horse across a ford with another horse ahead when the leading horse screamed and fell. By the time he came to this horse it was dead in the shallow stream and an enormous electric eel was swimming away. A rancher on the same island told us how cattle, meeting electric eels at a ford, are stampeded and cannot again in the same day be made to cross the same ford.

For experimental study the electric eel offers several advantages. The chief of these is that it lives well in captivity, as most of the electric species do not. On this account von Humboldt recommended it to Faraday. Another important advantage is that it can be kept out of water for some minutes without any change in its electric activity and for an hour or more without dying. It can, indeed, live longer out of water than under water, for its gills are ineffective and it has to come to the surface to breathe. This it does by gulping air, which it retains in its mouth and utilizes with the help of a peculiar breathing mechanism. This is doubtless an even greater advantage to the electric eel than to those who experiment with it. Otherwise it could not survive when in times of low water it is trapped in small and diminishing pools, where it sometimes lives only by hollowing out small depressions deep enough to keep its body covered with water.

Our experiments at the Aquarium were begun with three small electric eels, between 30 and 40 cm in length. One of them was taken from the water and laid in a wooden trough crossed at intervals of 5 cm by transverse wires. Dial switches were used to connect any pair of these wires to the terminals of an oscillograph. With the connection made, the fish was gently prodded and the oscillograph showed quick pulses, each lasting about 2 millisec, one following another to make a train of three, four or five. The pulses were unidirectional and the anterior contact on the fish was always positive with respect to the posterior one. The peak voltage found between any two points on the body of the fish was regular but was larger the farther apart were the points of contact along its length. The highest voltage obtained with any of these specimens was 200 v.



Oscillographic traces of the discharge of the electric eel: (*a*) a minor and five major discharges; sweep period, 50 millisec; (*b*) major discharges, superimposed by successive sweeps of the electron beam; sweep period, 4 millisec. [From *Zoologica*.]

When any portion of the posterior half of the length of the eel was included between the points of contact, pulses of about the same duration but of much lower voltage were observed. These minor discharges were produced singly and often without a stimulus to the fish. One of them always preceded the train of the major discharges. Their peak voltage was also regular between two points of contact, but was larger as one electrode was moved toward the tail, the other being held at the middle of the eel.

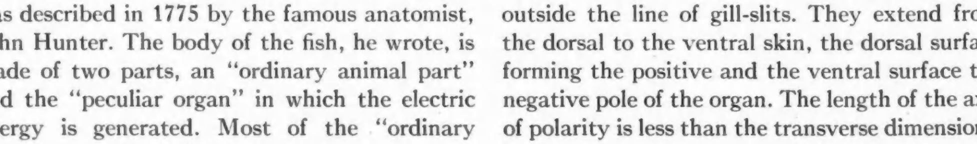
The utility to the fish of these two types of discharge was not evident at first. The minor discharge alone could give no great shock to an enemy or prey, and preceding a train of major discharges it could add little to their total effect. But listening to a telephone receiver when its terminals were in the water with the eel gave a probable clue. The minor discharge is given at short intervals whenever the eel is swimming. It seems likely that it serves as a warning to any possible enemy. Of course it would also warn any possible prey as well, but, slow swimmer as it is, the electric eel probably does not travel much in search of prey, waiting rather for its victims to come to it.

Generally the electric eels lie close together in the water. When one of them discharges, from alarm or to obtain prey, the others nearby close in. Their signal is the electric current in the

water, as is plain from the fact that they may be called by producing a current in any way. The behavior of the eel when a current is maintained between electrodes in the water is interesting to observe. He will first approach the nearer electrode, whichever it is. If it is the cathode, he may circle around it once or twice before swimming toward the anode. If the anode is not too far away, he will move to it and nose around it for some while. But if it is so far away that the current density is very weak between the electrodes, he will return to the cathode and proceed as before, giving up after one or two such attempts. More briefly, in a weak electric current the fish swims in the direction of increasing current density, whatever the direction of the current, whereas in a strong current he swims toward the anode. As one would expect from this, his behavior in an alternating field is indecisive. Some rough measurements indicate that the least potential gradient which the eel can detect in the water is between 0.2 and 0.02 v/m. This sort of telegraphic communication very likely compensates the electric eel rather well for his partial loss of sight, the better so in that he commonly lives in muddy water in which the clearest eyes could see no farther than a few feet.

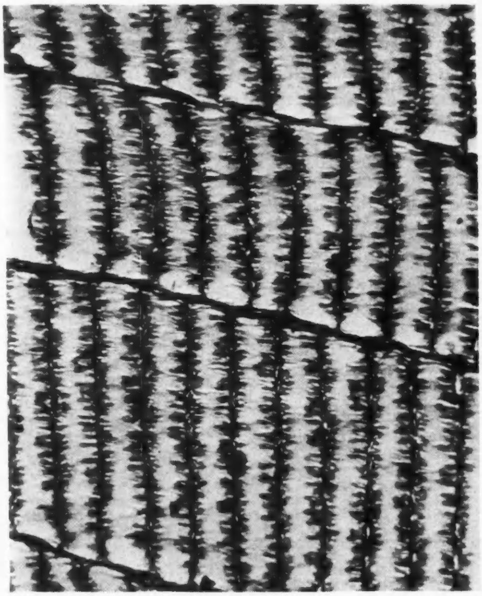
The production of two types of discharge is readily enough understood from the anatomical point of view. The anatomy of the electric eel was described in 1775 by the famous anatomist, John Hunter. The body of the fish, he wrote, is made of two parts, an "ordinary animal part" and the "peculiar organ" in which the electric energy is generated. Most of the "ordinary animal part," including all the vital organs, is found in the anterior fifth of the length of the eel. The posterior four-fifths contains most of the spinal cord, some long muscles above it, and under them the electric organs. Three pairs of electric organs are distinguished, each pair symmetrical on the right and left. The "large organs" have their anterior end immediately behind the visceral cavity and extend back, first with a nearly uniform cross section and then tapering to the end of the tail. Between them, just under the spinal column, is a long air bladder, relatively larger than in most fish. Under the entire length of the large organs and separated from them only by a thin wedge of muscle are the slender organs of Hunter. The third pair of organs, the bundles of Sachs, start about halfway down the length of the eel, first thickening and then tapering to the end of the tail. These are clearly the source of the minor discharge, which is observed with the oscillograph only when some portion of the length of these organs is between the electrodes. The large organs produce the major discharge. An irregular pulse sometimes seen in a train between the minor and the succeeding major discharges, we were at first inclined to attribute to Hunter's organs. It now seems more likely that this is merely an imperfect major discharge, and that Hunter's organs discharge with the large organs and are functionally a part of them, their structural separation being required only by mechanical necessity.

In the electric rays, *Torpedo* and *Narcine*, there is only one pair of organs. These fish have flat disk-like bodies, and the organs lie in the disk to the right and left of the body cavity, just outside the line of gill-slits. They extend from the dorsal to the ventral skin, the dorsal surface forming the positive and the ventral surface the negative pole of the organ. The length of the axis of polarity is less than the transverse dimensions, in contrast to the organs of the electric eel, in which the polarity is along the dimension of greatest length. Another marked difference between the rays and the eel is in the proportion of the body devoted to the electric organs. In the rays they comprise only about one-sixth



Drawing by Ralph Graeter

The electric eel with skin removed to show the electric organs. *A*, large organs; *B*, organs or "bundles" of Sachs, overlapping the large organs; *C*, Hunter's organs. [From *Bulletin of the New York Zoological Society.*]



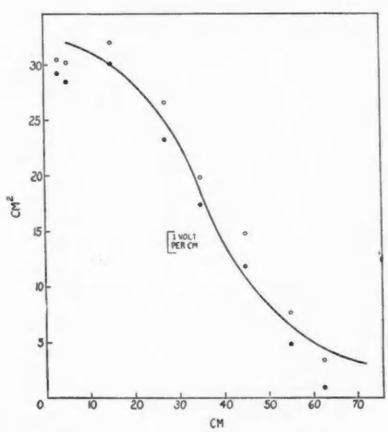
Longitudinal section of the large electric organ of the electric eel magnified about 50 diameters. The horizontal lines are the septa between layers of electroplaxes. The vertical lines are the boundaries between electroplaxes.

of the total weight, in the eel a little more than half.

The electric tissue is quite similar in all these fish and quite different from any other tissue. It is gelatinous, and if the fluid is pressed out only a tough web remains. This web gives the organ its structure, which is most regular in the electric rays. In them the organ is made of several hundred small columns or prisms, something like the cells of a honeycomb, each extending from one pole of the organ to the other. A section of one of these columns, under a little magnification, is seen to be a pile of similar units. These are the electric plates, or electroplaxes. A higher magnification shows the branched ending of a nerve fiber on the ventral or negative surface of each plate. Such nerve endings are found on the electroplaxes in all the electric species, and the relation between the place of the nerve ending and the polarity is the same in all.

The electric organs of the eel, though very different in shape from those of the rays, are generally similar in structure. They are divided by horizontal septa into layers which correspond roughly to the columns in the organs of the rays. These layers are divided by thinner vertical septa which, like the horizontal septa, run lengthwise along the organs. The faces of the electroplaxes are perpendicular to the two sets of septa, and the pile of electroplaxes thus forms a series along the length of the organ, which is the axis of polarity.

In the rays, the electroplaxes are of about the same thickness all along the column. In the electric eel, the thickness of the plates is very variable along the organ, increasing, in the large organ, as the cross section of the organ diminishes. The increase is regular, the thickness of the electroplax being rather closely in an inverse proportion to the cross-sectional area, so that the volume of a transverse section of the organ one electroplax in thickness is approximately uniform along the organ. If the organ might be thought of as being first formed with a uniform cross section and of plates all of one thickness, and then pulled to its tapering shape without changing the volume of a plate, the result would be like that which is observed. Of course, the growth of the organ is actually no such process as this, and it remains a puzzle why the structure should be as it is found.



Graph showing the proportionality between cross-sectional area and peak voltage per unit length in the organs of the electric eel. *Dots:* large organs, cross-sectional area *versus* distance along organ from anterior end. *Circles:* large organs and Hunter's organs, cross-sectional area *versus* distance along organ. *Curve:* peak voltage per unit length (to scale shown by bracket) *versus* distance along organ. [From *Zoologica.*]

The relation between the thickness of the plates and the cross section of the organ at least explained one observation which we made earlier and found surprising, that the voltage per unit length along the organ is proportional to the cross-sectional area. The two observations taken together indicate that the voltage per electroplax is, at least roughly, uniform along the organ. The order of magnitude of this voltage, 0.05 to 0.15 v, is the same in each of the three species we have studied, though, in the marine species especially, the voltage varies a great deal with the condition of the fish and may be much less than 0.05 v per electroplax in a fish in poor condition.

It was pointed out long ago by duBois-Reymond that there is a connection between the shape of the organ and the electric conductivity of the water in which the species lives. In comparing the electric eel with either of the rays, it is seen that the array of electroplaxes is relatively more in series in the eel and more in parallel in the ray, as it would be if the arrangement were made to match the resistance of the organ to the resistance of the external circuit through the water, since the eel is a fresh-water fish and the rays are marine species. A comparison of the various electric species shows that this is a general distinction between fresh-water and marine varieties, and it becomes clear that the elongate body of the electric eel and the flat body of the ray are, each in its environment, best suited for the development of electric power. There remains, however, a puzzling exception. Several species of skate are weakly electric. They are marine fishes, related to the rays, and have flat bodies, but their electric organs are found in the tail and are spindle-shaped, as we should expect to find them in fresh-water species. These organs are in a low state of development, and it is not known whether they are evolving or disappearing. There are reports, not too well authenticated, of fresh-water electric fish of the ray family in the far interior of Brazil. If these could be found, their comparison with the marine electric rays and skates would be interesting.

Oscillographic trace obtained when the discharge in an anterior segment of the large organ supplies the sweep voltage for the discharge in a posterior segment. The traces of several discharges are shown superimposed. The large black spot is the overexposed image of the fluorescence of the undeflected electron beam. [From *Zoologica*.]

The organs of the electric eel never quite develop their maximum voltage, because the discharge does not reach its peak at the same instant all along the organ. This is shown by connecting an anterior part of the organ to the horizontally deflecting plates of the oscillograph and a posterior part to the vertically deflecting plates. If the discharge were exactly synchronous in the two parts, the oscillographic trace would be a straight line. Actually, it is a loop, which is wider the greater the distance between the two segments connected to the two pairs of deflecting plates. From the shape of the loop it is possible to calculate the time the discharge takes to pass from one segment to the other and hence the speed with which the discharge is propagated along the organ. The speed is not uniform, at least in the large organ where it has been measured, but decreases toward the tail. In different specimens and different parts of the organ, speeds from 2500 to 450 m/sec have been measured. The least of these speeds is much higher than those commonly found for the propagation of impulses along nerves. Nevertheless, it is certain that each part of the organ is activated by a nerve branching from the spinal cord to that part. For if the cord is cut the discharge takes place in all parts in front of the injury and none behind. It is not clear how this high rate of propagation of the discharge along the organ is obtained. It would not necessarily seem to require so high a speed of the nervous impulse along the spinal cord. The nervous impulse might travel much more slowly than the discharge if there were some way in which the discharge at the anterior end could be delayed relative to the discharge at the posterior end.

The same method as was used to show the slight lack of synchronism in the discharge at different points along the organs of the electric eel can be used to show that in the electric rays the two organs discharge at almost exactly the

same instant. When there is any detectible time lag, it is only about 0.1 millisec.

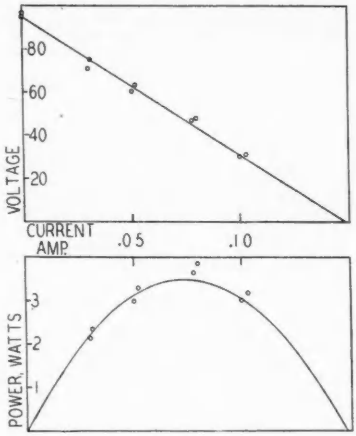
All the voltages thus far mentioned have been those measured without drawing current from the electric organs except what existed in the body of the fish itself. When a current is drawn through an external resistance, the voltage is lowered. A graph of the peak voltage *versus* the peak current is linear, as it would be if the current were attributed to an electromotive force in a circuit made up of resistances subject to Ohm's law. The intercept of the graph on the axis of voltage is the maximum voltage developed externally, which, in the organs of the rays and in short segments of the organs of the eel, is probably not much less than the electromotive force. The intercept on the axis of current is the maximum external current, as would be obtained by a complete short circuit of the organ.

The graph of the externally developed power *versus* the current is readily constructed from the graph of voltage *versus* current.

For the only sound specimen of *Torpedo occidentalis* on which we have made electrical measurements, we found a maximum voltage of 220 v and a maximum power, in both organs together, of something more than 6 kw, corresponding to an external current of about 60 amp. The electric organs of this fish had a mass of about 4 kg, so that the tissue had a maximum power of about 2 hp/kg. The measurements were crude, but the orders of magnitude are probably right. It must, of course, be remembered that these are all instantaneous values. The average values would be considerably less even during a period of intense electric activity, and, since the fish does not discharge often, the average values over periods of hours would be very much less indeed.

Narcine brasiliensis is a much smaller fish, the mass of an adult being generally less than half a kilogram. Its electric activity resembles that of *Torpedo*, the differences being those that might be expected from the difference in size.

The electric eel may grow to a length of more than 2.5 m. Even without reaching so great a length it may attain a voltage, on open circuit, of 500 to 600 v. The largest current it produces, however, in even the thickest part of the large organ, is probably never more than 1 amp.



Graphs of voltage *versus* current and power *versus* current in a part of the length of the large organs of an electric eel.

The electric organs of all species must derive their power ultimately from the consumption of oxygen. In the species we have observed, the supply of oxygen seems to be well provided by the nearness of the organs to the gill-slits in the rays and to the air bladder in the eel. The electromotive force itself is most likely produced by a difference in concentration of some salt on the two sides of a boundary of the electroplax. Animal and plant membranes generally show some selective permeability. When the membrane discriminates between uncharged molecules, it produces an osmotic pressure; when it discriminates between ions, as some of them do, the result is a concentration potential.

If the chemical reactions intermediate between the oxidation at one end and the electromotive force at the other can be traced, it may add appreciably to our knowledge of general physiology. For there is general agreement among physiologists that the electric activity of these fish is fundamentally identical with the processes occurring in nerve tissue during activity. In the electric organs the electric effects are amplified to the point where their measurement is comparatively easy, and the chemical reactions must occur on a scale much larger than that found in nerve.

How the nervous impulse releases the current in the organ is still far from clear. The simplest picture would be to think of it as closing a mul-

titude of switches to join the electroplaxes in series. The drop of the electric resistance of the organ which is found to accompany the discharge gives some support to this supposition. But the electric network of the organ may be a complex affair, and, even if the discharge were described in familiar electrical terms, this would be only a beginning of the problem of real interest, which is to trace the molecular changes by which the energy is generated and released.

It seems fitting to conclude this slight account of the varieties of electric fish with a description of the artificial torpedo of Cavendish and of the memoir he published on it. Now seldom noticed, it was at one time celebrated, and justly so, because in it several of the fundamental concepts of electricity were more clearly formulated than ever before. Cavendish himself evidently considered it among his chief contributions to the knowledge of electricity.

"I am aware," wrote Clerk Maxwell, "of only two occasions on which Cavendish, after he had settled his own opinion on any subject, thought it worth his while to set other people right who differed from him." One of these occasions was when he invited a group of his colleagues—if so solitary a man can be said to have had colleagues—among them, John Hunter, the anatomist, and Joseph Priestley, the chemist, to witness his research on *Torpedo*. These were the only visitors, so far as his papers show, ever admitted to his laboratory. He published an account of these experiments in 1776, when he was 44 or 45 years of age. He had published one electrical paper earlier, and, although he lived to be 78, he never published another.

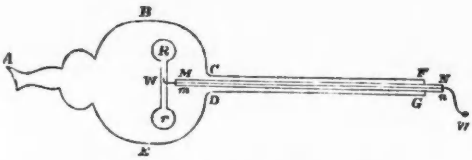
The background of this research was as follows. Until just before that time no one who had described the shock of electric fish seems to have recognized it as an electric shock. In a novel, *Oroonoko; The Royal Slave*, written by Mrs. A. Behn and published in London in 1688, the scene being Surinam or Guiana, an electric eel figures in one of the many dramatic episodes. Here the numbness caused by the shock is attributed to a supposed quality of extreme cold in the fish, a late echo probably of the physics of Aristotle, according to which all the properties of matter were ascribed to combinations of four primary qualities—hot and cold, wet and dry. In somewhat later writings, electric fish were supposed to give their shock by a muscular stroke too swift to be seen or by the emission of torporific particles.

In 1775, however, John Walsh described some observations on *Torpedo* which indicated that its shock was electric. Some remained unconvinced, and it is not hard to see why when we consider the state of electrical knowledge at that time. The notion of "degree of electrification," or, in modern terms, *potential difference*, was not yet clearly differentiated from that of *quantity of electricity*, though Cavendish in his earlier paper had begun to make the distinction. Conductors and insulators were known, but the idea of *resistance* was still so confused that a widely held opinion maintained that the electric fluid followed the path of least resistance to the complete exclusion of paths of greater resistance. The voltaic cell and pile and the thermoelectric current were unknown, and the concept of electromotive force had not emerged. The only known electric effects were electrostatic, and these were obtained only with careful insulation. It was natural therefore to doubt whether any phenomenon originating in so good a conductor as the body of a fish and taking place in sea water could possibly be electrical. A contemporary, Thomas Ronayne, said of Walsh's hypothesis:

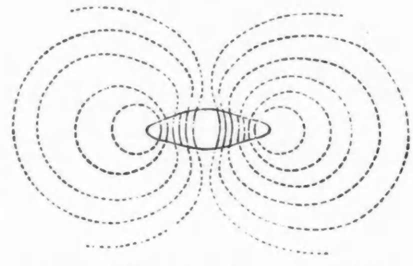
> . . . if *that* could be proved, he does not see why we might not have storms of thunder and lightning in the depths of the ocean. Indeed, I must say, that when a Gentleman can so far give up his reason as to believe the possibility of an accumulation of electricity *among conductors* sufficient to produce the effects ascribed to the Torpedo, he need not hesitate a moment to embrace *as truths* the grossest contradictions that can be laid before him.

Such was the background of these experiments of Cavendish. Perhaps their most curious feature is that there is no evidence that Cavendish ever handled or even saw a live torpedo. Fish of this genus are not found on the English coast, and they do not live in captivity. His experiments were conducted entirely with models. He depended on the description given by Walsh of the discharge of the fish, and his purpose was to show that the discharge could be imitated with devices known to be electrical.

His first model was made of a piece of wood



The artificial torpedo of Cavendish. [From *The Electrical Researches.*]



Lines of current through and around the electric organs of *Torpedo* as conjectured by Cavendish. [From *The Electrical Researches.*]

cut to the outline of a torpedo—fins, tail and all. On this were fastened pewter plates, representing the faces of the electric organs, and the whole was covered with leather in imitation of the skin of the fish. The model was well soaked in brine of the salinity of sea water to give it a conductance comparable to that of the live fish. Glass-insulated leads carried the current from a battery of Leyden jars to the pewter plates. The battery was made of 49 thin-walled jars in seven rows and had, with all the jars in parallel, a capacitance of 321,000 "globular inches of electricity" in Cavendish's units, or $0.45\mu f$, an enormous value for that time.

This battery was charged by an electric machine and discharged through the artificial torpedo and the hands of an observer on the faces of the organs. With the torpedo either in air or salt water it was possible to adjust the charge so as to match the shock of the real torpedo as Walsh had described it. But when the adjustment was made with the model in air, the discharge in water gave a shock that was barely perceptible, contrary to what was found with the living fish. And if the charge was so increased as to produce in water the shock of the living fish, then the shock in air would greatly exceed that of the fish.

Cavendish concluded from this that the wooden body of his model was not as good a conductor as that of the fish, and he made another model in which the body consisted of several thicknesses of sole leather, sewed together and soaked in brine. The shock of the fish in air and in water was now well imitated by the model with the same charge on the battery. In another respect, however, the correspondence between the model and the live fish was less exact. The discharge of the real torpedo, so far as was then known, would not pass across any interruption of the circuit, even the thin insulating film separating the links of a chain. But the discharge of the battery, when it was large enough to produce a shock as severe as that of the torpedo, could pass along a chain of several links. Here Cavendish introduced the distinction he had made between *potential difference* and *quantity of electricity.* He showed that a small capacitance, charged to a potential difference sufficient to produce a given shock, would discharge through a chain of more links than would a large capacitance charged to the lower potential difference required to produce the same shock as the other. He concluded therefore that if his battery had been still larger he could have produced the shock of the real torpedo with a potential difference low enough not to spark across even the gap between two links of a chain.

Finally, he took up the question whether there could be room enough in the fish for a condenser of so great a capacitance. He supposed, as in modern theories of nervous impulse, that the boundary of the electroplax is a dielectric with charge at its surfaces, and he used the anatomical study made by Hunter to estimate its possible capacitance. His numerical result is of minor interest. He had only a very large upper limit to the thickness of the membrane, and he treated the electroplaxes as if they were all in parallel, rather than in a series-parallel array. His conclusion was that the electric organ might have a capacitance 14 times that of his battery.

In spite of this seemingly satisfactory result of the calculation, he offered an alternative explanation of the electric discharge of the torpedo, which is perhaps the most remarkable part of the entire paper. He said:

> . . . perhaps it is not necessary that there should be anything analogous to a battery [of Leyden jars]

within it. The case is this; it appears, that the quantity of electric fluid, transferred from one side of the torpedo to the other, must be extremely great; for otherwise it could not give a shock, considering that the force with which it is impelled is so small as not to make it pass through any sensible space of air. Now if such a quantity of fluid was to be transferred at once from one side to the other, the force with which it would endeavor to escape would be extremely great, and sufficient to make it dart through the air to a great distance, unless there was something within it analogous to a very large battery. But if we suppose, that the fluid is gradually transferred through the electrical organs, from one side to the other, at the same time that it is returning back over the surface, and through the substance, of the rest of the body; so that the quantity of fluid on either side is during the whole time very little greater or less than what is naturally contained in it; then it is possible, that a very great quantity of fluid may be transferred from one side to the other, and yet the force with which it is impelled be not sufficient to force it through a single interval of the links of a chain.

Here is not only the distinction plainly made between potential difference and quantity of electricity, but also, before the discovery of the voltaic cell or thermoelectricity, a clear anticipation of the idea of electromotive force. In this work of Cavendish we have one of those rather rare instances—of which the contribution of the physiologists to the discovery of the conservation of energy is the most notable—in which the study of a biological phenomenon contributed to the clarification of fundamental concepts in physics.

REFERENCES AND ACKNOWLEDGMENTS

Anything like a complete bibliography on the subject of electric fish would be of a length disproportionate to the length of this article. A rather long one has been given by Coates, Cox and Granath in *Zoologica* (N. Y. Zool. Soc.), Vol. XXII, Part 1 (1937).

For the historical material I have drawn chiefly on:

The electrical researches of the Honourable Henry Cavendish, ed. by Clerk Maxwell (Cambridge, 1879);

Faraday's *Experimental researches in electricity* (London, 1839) and *Diary* (London, 1932–1936);

The article by Francis Gotch on "The physiology of electric organs" in *A textbook of physiology*, by E. A. Schäfer (London, 1900);

Electric eel calling, by Shelby Shackelford (New York, 1941);

Fishing from the earliest times, by William Radcliffe (New York, 1921).

The observations in which Mr. Coates and I have been associated are described in a number of articles published or soon to be published in *Zoologica*, the *Bulletin of the New York Zoological Society*, the *Journal of General Physiology*, and the *Journal of Neurophysiology*, with a number of collaborators: Dr. C. M. Breder, Dr. M. Vertner Brown, Miss Janice Cutler, Dr. L. P. Granath, Dr. A. L. Machado, Mr. R. S. Mathews, Dr. D. Nachmansohn, Mr. W. A. Rosenblith and Dr. G. M. Smith.

The figures from the publications of the New York Zoological Society are reprinted with the kind permission of the editor, Mr. William Bridges.

The reference to *Oroonoko; The Royal Slave* I owe to my colleague, Professor W. R. Ranney, Department of English, New York University.

It is a pleasure to be able again to express thanks to the Doctor Simon Baruch Foundation for a grant in aid and to the staff of the Museu Goeldi of Para, Brazil, and many others in that place for their generous help to our expedition there.

A FEW weeks ago, I spent three or four fascinating hours in two of the great industrial research laboratories. I give you my word that if I could turn the clock back and have a chance to do it all over again, I can't think of anything I would rather do than serve on the scientific frontier with those men. Some of their experiments were described to me, but alas, they meant nothing but a lot of abstruse chemistry and physics. Yet when they began to interpret to me what they were looking for, what they were trying to find, what they were hoping to accomplish through it, I began to take fire. I said to my guide, "Well, I suppose that out of all these experiments you are doing, you hope you will find a better product or a better process?" And he looked at me with compassion for a minute and said, "Why, sir, that is the one thing we are *sure* of. We *know* we shall find a better product or a better process."—WILLARD CHEVALIER, Publisher of *Business Week*, in J. Eng. Ed. **33**, 202 (1942).

The New Spirit in American Physics*

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WE are here to pay homage to a personality and a career, to those of an individual and to those of his type. Floyd K. Richtmyer (1881–1939) was not preeminent as a mathematical or theoretical physicist—though he was thoroughly grounded in mathematics and could use mathematical operations for his purpose. He was not a genius in experimental physics though he made substantial contributions to the domain of x-rays. He was not a worker of magic, he was not a peer in popular exposition. But as a teacher of fundamental physics, as dean of a graduate school of science, as an author of an important textbook—*Introduction to Modern Physics*—as founder and editor of physics journals, as an organizer and officer of our physics societies, he was a leader in the new spirit in American physics. His characteristics were radiant zeal and abounding activity, zeal not emotional but based on knowledge; activity directed and purposeful. Today we speak of our nation as going "all out" for war. Richtmyer went "all out" for physics.

I have spoken of the new spirit—the twentieth-century spirit in American physics. It is not a matter for wonder that no contribution to our knowledge of the physical world came from America before the end of the nineteenth century. (Franklin's scientific work was of relatively small moment. Rumford carried on experiments and set forth his philosophy in Europe.) The Pilgrims were landing in America just after Galileo was made to "abjure, curse and detest the heresy of the movement of the earth." Harvard College had been founded 50 years when Newton informed the infant human race that all the matter of the universe was held together by forces identical with those which caused an apple to fall to the ground. The Colonists in America, living a hard frontier life, had no leisure for scientific experiments, but in Europe growth in physics continued, gradually during the eighteenth century, at an accelerated pace during the nineteenth. Oersted, Ohm and Faraday opened up the great realm of electricity. Had Joseph Henry been more active in publication his would have been the first American name to achieve distinction in physics. (The discoveries of a hermit scientist die with him.) In the middle of the nineteenth century, the law of the conservation of energy was established. Later Maxwell, a giant among men, made light an electrical phenomenon and postulated the existence and properties of electric waves. Only a dozen years before the twentieth century these waves and the photoelectric effect were discovered by Hertz. The physicists of the world viewed the great structure which had been reared and pronounced it nearly complete. Perhaps more than one physicist pictured the condition of physics thus: "it can now, with assurance, be stated that all the great discoveries in physics have been made—from now on progress will lie in the seventh place of decimals." This statement has been attributed to various authors. I only know that in the spring of 1895 I received a circular outlining the program in physics in an important American university and containing that statement. It had been written by or at least sponsored by one of the foremost of American physicists.

Thus in the spring of 1895, we were told that there were no new realms to be opened up, no glorious adventures in physics. A man would have to be a mathematical giant or a genius in experimental skill to achieve recognition. Then there occurred a series of earthquake shocks—shocks that shook the world of physics, that shook the entire world. On December 28, 1895, Röntgen announced the discovery of a strange radiation to which he gave the name x-rays. This triggered off the discovery by Becquerel of uranium rays in 1896, and this in turn led Madame and Pierre Curie to a glorious triumph in the discovery of polonium and radium in 1898. In the preceding year J. J. Thomson made clear the nature of cathode rays by the final identification of the electron. (Faraday nearly discovered it 60

* The second Richtmyer Memorial Address of the American Association of Physics Teachers.

years earlier; Johnstone Stoney in 1874 gave it the name it now has and made an approximate computation of its charge. Henceforth it was out in the open and could be produced at will.) No difficult mathematical operations, no measurements involving the seventh place of decimals were necessary in these great discoveries. But when we come to the next great advance—the proposal by Planck in 1900 that radiant energy was not continuous but was tied together in bundles each proportional to the frequency—we do meet mathematical operations of considerable difficulty and obscure concepts lacking apparent reality. Moreover, Planck was under compulsion to fit his theory to the laws of blackbody radiation, empirical laws arrived at through a long series of experiments of the highest precision.

Along another line it should be noted that, in 1895, it was discovered that an inert gas—argon—constituted nearly 1 percent of our atmosphere. (The fact that there was a 1-percent residue of some sort was discovered by Cavendish 100 years earlier.) In 1898 the other inert gases in the atmosphere—neon, krypton, xenon—were discovered. In 1895 helium was isolated from uraninite, a fact of very great importance when, a few years later, attempts were made to analyze the phenomena of radioactivity.

No other period of five years can rank with these years in their revolutionary upsurge of discoveries in physics. They set the world on fire. But no American physicist participated in them. In the fall of 1899 the American Physical Society—our first national society of physicists—was founded at Columbia University. The two leading physicists of America, Rowland and Michelson, were elected president and vice-president. There were about 30 in attendance at the first meeting, only a fraction of whom could qualify as physicists. The total membership during the first year was 59; 40 years later it was about 4000. The number of papers presented at the first meeting was three, at the second six, and now before the various sections during a year the number is several hundred.[1] Moreover, there are the numerous offspring or collateral branches listed in Table I; for example, the Institute of Radio Engineers with its 12 sections and 5000 pages of scientific papers.

TABLE I. Physics societies.

Society	Year founded	Members: First year	Members: 1941
American Physical Society	1899	59	4000
Institute of Radio Engineers	1912	109	7020
Optical Society of America	1916	74	1200
Acoustical Society of America	1930	512	850
American Association of Physics Teachers	1931	494	867

I desire to discuss very briefly these great discoveries of the closing years of the nineteenth century, discoveries that let loose a new spirit, especially among American physicists.

Let us return to x-rays. It is commonly thought that this discovery was purely accidental. But Röntgen was 50 years old at the time and had already published about 100 papers giving the results of his various experiments. These showed constant, intense activity. It was no accident that he was working on the discharge of electricity through a gas. This was the realm of great interest for physicists. He was acquainted with and was following up the work of Crookes, Hittorf, Lenard and others. He had made the discovery on November 7 but kept his great secret guarded from everyone until, after having made certain the existence of the rays and their chief properties, he presented his historic paper on December 28. If he had not made the discovery at that time some other physicist soon would have made it, but that physicist would in all probability have possessed the same characteristics as Röntgen—he would have had a thorough foundation in physics, a knowledge of the work of his predecessors, a scientific imagination, abundant zeal, boundless energy directed towards the scientific end in view.

The discovery of x-rays had a number of amazing results. No other scientific discovery ever received so much publicity. Within six months more than 1000 news items and editorials appeared in newspapers scattered over the world. It was ridiculed and praised. Playful people sent to their friends what they claimed to be their latest photograph, an outline of the skeleton of a

[1] The great increase in the number of physicists engaged in research in industrial laboratories is a story into which we cannot enter.

frog or a caricature of a human skeleton. Squeamish ladies hesitated to appear on the street; they might meet a physicist with an x-ray tube. On the other hand, physicists all over the world were ordering induction coils, x-ray tubes, vacuum pumps. The orders could not be filled for months. The first voltages used were pulsating, rather uncertain in value and of relatively small magnitude. Then came the demand for definite, continuous voltages of higher and higher values, until now we have x-ray machines of millions of volts, constant in value. (The new induction accelerator will produce pulsating, very high voltages of the order of 50 or 100 million volts.)

Christopher Columbus discovered America, but in his wildest dreams he never pictured the American continent of today; it was beyond the power of his fifteenth-century mind to visualize even this part of the continent with its vast control of power on land, on and under the sea and in the air. No physicist in the world had foreseen the existence of x-rays. Even after their discovery no one could foresee the great role they would play in science, surgery, industry. The tenfold increase in the realm of radiant energy, the creation of new branches of science, the applications in all of science and in many industries, the saving of human life—these were some of the results. It is probably true that there are a million people alive in America now who would not have been alive had x-rays not been discovered. So far seven investigators have received the Nobel prize for work in x-rays—Röntgen, the first recipient of the prize; Laue; the Braggs, father and son; Barkla, Siegbahn and A. H. Compton.

Next consider the electron. What shall we say about its final identification by J. J. Thomson in 1897? Note that both these discoveries—x-rays and the electron—came from a study of cathode rays discovered 20 years earlier by Crookes. For the first time it was known that all atoms have one common constituent which can be taken away from them. Richardson's work in 1900–1903 with hot wires gave us the electron tube. But it would be impossible here to picture the vast extension of physics, indeed of all science and of industry, owing to the discovery of the electron.

Note the timeliness of the discoveries of x-rays (1895) and the electron (1897). In the analysis of the phenomenon of radioactivity discovered in 1898, two of the "radiations" emitted by a complex radioactive source were at once identified; one was a stream of electrons, the other was similar to x-rays. But the third, tentatively called the *alpha-rays*, what was that strange radiation? And here opens a chapter in American physics of which we are apt to lose sight. In 1898 a 27-year old New Zealander was appointed research professor of physics in McGill University. Ernest Rutherford began there a career that was to place him at the very top of the world's physicists. In the energizing action which he exerted on our work in science he himself was like a radioactive source. An indication of the activity in Canada at the beginning of the century is seen in the fact that of the 17 papers given before the American Physical Society during the Christmas week 1902–1903 (the first meeting to be reported in the *Physical Review*) five were from two Canadian universities, McGill and Toronto. In perhaps one of the most important papers ever to be presented before the American Physical Society, "The Magnetic and Electric Deviation of the Easily Absorbed Rays from Radium," Rutherford showed that the particles composing the alpha-rays must be either helium atoms with two units of charge or hydrogen molecules with one unit. Rutherford inclined towards the former view, but no clear proof was obtained until 1908, as a result of the Rutherford and Royds experiment and by the equally convincing experiment of Rutherford and Geiger in which it was proved that the charge on an alpha-particle was two units. Notwithstanding the fact that the nature of the alpha-particle was not completely known, Rutherford and Soddy in 1903 drew up the family relationship for the first five members of the radium genealogical tree. It was heroic, in fact it was considered foolhardy, to propose that one element spontaneously changed into another. Many members of the McGill science faculty were afraid that the University would be placed in a ridiculous light by the views set forth by its exceedingly active youngsters. One of the world's foremost chemists of that time declared that "Chemists have no evidence of atomic disintegration on the earth." Indeed it was not until 1908 that Oswald, the leading physical chemist of the world, reluctantly admitted that atoms and

molecules, up to that time mental abstractions to chemists, had an objective existence. Behold the transformation that has taken place in 40 years. Transmutation of the elements, then rejected as a foolish dream of alchemists, now has been carried to such an extent that every chemical element has been changed over into others. In place of the 90 atoms known to physicists in 1900, there are now about 280 stable atoms and 370 radioactive forms, or a total of 650, together with an innumerable number of different energy states.

Although Rutherford inclined to the view that the alpha-particle was a helium atom—he was supported in that view by Ramsay's discovery in 1902 that helium was found in uranium and thorium minerals—he was, before 1908, still puzzled.[2] I had considerable correspondence with Rutherford during those years concerning the nature of the alpha-particle. In answer to a letter from me urging the acceptance of the hydrogen molecule or of an unknown atom of mass two, he wrote (Nov. 20, 1906):

> In regard to the alpha particle I hold no fixed opinions. . . . You know that an alpha particle vanishes like a ship in the night at full speed when it ought to go on ionizing. . . . I am looking for methods of throwing further light on the question. . . . "What is an alpha particle" is I think one of the most interesting conundrums that science has been confronted with for some time.

Had heavy hydrogen been known at that time it would have been a strong competitor as an answer to the question.

To show the very great care which had to be exercised by those working in the radioactive field, I desire to introduce the following personal item. In March 1904, Rutherford gave a lecture at Dartmouth College on radium. He had brought with him in a small lead box about 20 mg of radium bromide. Before the lecture he desired to get the radium salt into a small glass tube in order to pump off the "emanation," as he then called the gas now known as *radon*. He was given a piece of good paper about two inches square, slightly creased. He poured the radium on to the paper and coaxed it into the glass tube, using a pen knife to scrape in the final particles. I folded the paper, put it into a metal pill box, and placed this in a lead box. That piece of paper, now a brown powder owing to constant bombardment by millions of alpha-particles, has been the radium supply of our laboratory for these nearly 40 years. It discharges an electroscope, it makes an alpha-counter bark. By means of it we can measure the range of certain alpha-particles in air or the equivalent range in thin films of mica. It will drop to half-activity in 1600 years. To us it is worth many times its weight in gold. Rutherford proved later that 1 gm of radium gives out 3.7×10^{10} alpha-particles per second. We can compute that 10^{-6} oz would supply 10^{6} particles per second. And we can identify and count one particle. The white paper turned to brown powder is mute evidence of that fact.

The alpha-particle gave us the nuclear atom model and the natural, then the artificial, transmutation of the elements. And this led to the designing of high power, long range atomic guns. In this field Americans excel. The newest atomic gun, the $1,500,000 cyclotron, must be operated from a distant trench, for it is nearly as dangerous to be behind or at the side of this gun as to be in front. Compare with this cost that of the brown paper powder in the Wilder Laboratory of Dartmouth College.

One cannot touch on the topic of radioactivity without paying tributes to Madame Curie, the brilliant young woman of the iron will who initiated the research, and to Pierre Curie who, after 15 years of plodding toil in research came to the field that gave him his greatest fame. Yet during those 15 years he made many contributions to physics. His name is attached to more effects or laws than is that of any other physicist —the *curie*, the *Curie balance*, the *Curie constant*, the *Curie law*, the *Curie point*, the *Curie-Weiss law*.

The discoveries of x-rays, the electron, radioactivity and the quantum opened up vast vistas which so allured physicists in America that the United States has jumped from the fifth or sixth place in physics to the leadership of the world. But other nations have been climbing too. Japan, Russia and India now probably would be placed in succession after America, England and Germany. And what are the implications of this amazing growth in science? To see how the point

[2] Note that helium, an inert gas, only recently discovered, was almost an unknown element. Its atoms had never been electrified as in electrolysis.

of view has changed concerning the importance of scientists to a nation, let us go back to the closing years of the eighteenth century. For comparison purposes note that Harvard was founded in 1636, William and Mary in 1693, Yale in 1701, Pennsylvania in 1740, Columbia in 1754, Brown in 1764 and Dartmouth in 1769. Homer, Virgil, Shakespeare—literature, history, the arts—the study of these was flourishing; but in science it was still taught that there were four elements of which the universe was composed—fire, water, earth and air. But in 1784 Cavendish proved—marvel of marvels—that water was not an element; it could be broken up into two gases. However, it was still held that phlogiston (heat) plus water produced earth. Physics, with its Galileo and Newton, was a century ahead of chemistry, and both were centuries ahead of folk customs and beliefs. A blindfolded man carrying a forked stick could locate water far below his feet by the twisting of the stick; in fact, it is still being done. Mesmer in Paris, who knew everything that was to be known about animal magnetism, was curing the crowds who flocked to him by having them sit in a darkened room around a vat from which issued colored vapors, while he, connected by a light chain to the vat, would fill each one with magnetism by touching the invalid with a wand. Thus magnetism, flowing from the vat through the metal chain, passed through the magnetic body of the high priest and thereby obtained curative properties. We still have shrines in which invalids supposedly are cured of whatever ailments inflict them by touching a mysterious object in the hands of a modern clerical Mesmer.

Antoine Lavoisier[3] (1745–1794), chemist and man of affairs, vigorously refuted the virtues of Mesmerism and of the divining rod. He introduced scientific methods into agriculture in France both as to cultivation of crops and the breeding of cattle and sheep. He loaned money to the peasants without interest. He worked for the free education of all children. He was an unselfish public benefactor. But because he was a member of La Ferme Générale, the body which bought the concession for collecting the taxes, he with all its other members was condemned to death by the Tribunal of the Revolution. In answer to a petition in his favor setting forth the fact that he was a scientist whose discoveries had been of great benefit to the nation, the head of the Tribunal answered, "the Revolution has no need of scientists." Some historians claim that this statement is of doubtful authenticity. We cannot summon witnesses who heard the remark to give evidence on this point. We do not have a film record of face and voice to support the statement. But it is not inconsistent with numerous known facts. Indeed it would appear that even in recent years, France has had little need of scientists. As evidence note the fact that Pierre Curie at the age of 35, as chief of the laboratory of the Paris School of Physics and Chemistry, had a salary of $55.00 a month—less than one quarter of the amount now paid in America to a man who performs a simple routine job in a factory that might conceivably be done electrically for a few cents a month. One man-power is equivalent to about 25 w, but a 1-kw machine in continuous operation would do the work of 120 men in three shifts of 40 men each, working continuously.

Yes, the Revolution has no need of scientists. The sit-down strikers of France or America have no need of scientists. Yet all factories owe their existence to science. All industrial progress from the stone age to the present time is due to science. Nations in their hour of greatest need call upon scientists to save them. Charles, Elector of Bavaria, called on Count Rumford when "Beggars and vagabonds of both sexes and all ages, natives and foreigners, swarmed over the land, lining the roads, robbing houses, stores, workshops and churches." Rumford instituted "CCC brigades;" he made all soldiers, for physical exercise and recreation, work in gardens. He set forth and followed this principle, "All sums of money or other assistance given to the poor in alms, which do not make them industrious, never can fail to have a contrary tendency, and to operate as an encouragement to idleness and immorality." It would be well if the leaders in our

[3] Lavoisier's *Traité Elémentaire de Chimie* (1789) marks the beginning of modern chemistry since it rejected some of the four elements of the ancients and dealt with 33. Among these, however, were light and caloric, also lime, alumina and other compounds. The name "Father of chemistry" was given to Lavoisier as it had been given to Boyle a century earlier. But it cannot be said of Lavoisier as it had been said of Boyle that he was both the "father of chemistry and brother to the Earl of Cork."

public life would get acquainted with that principle and follow it.

For some time after the revolution of 1917, Russia had no need of scientists. These were merely members of the intelligentsia and suffered the fate of that class. But during the past 15 years, the Russian Government has encouraged science in every way and has given scientists the most generous treatment. Many research centers have been established, not only in the chief cities but in numerous cities unheard of until recent years. Important scientific periodicals printed in English come to us now from Russia. Science is the important subject in all the many schools. The superb showing of the Russian Army is in part an evidence of these facts.

Japan's progress in science during these 40 years has been phenomenal. She has come from nowhere up to about the fourth place in the list of nations. In some applications of modern physics she is very near the top. The physicists of America knew that Japan would not be an adversary that would follow primitive methods in warfare. She has broken away from medievalism. Her soldiers do not wear kilts; they do not wear hobnailed shoes if light rubber-soled shoes are better. She does not pass out rations of rum to the members of the navy. And if her scientists ruled her, Japan very likely would take her place quietly, peacefully, among the nations.

England has need of scientists. In September 1940, England passed through a most critical period. She had only 300 first-line Spitfires and Hurricanes to fight off a horde of Luftwaffe. But a device due to physicists stepped up the power of the English planes 20 times, and 185 of the Luftwaffe were shot down in one day. Another device made the German magnetic mine nearly harmless. Small wonder that there came out of England the statement, "a hundred physicists are worth a million soldiers." This ratio is in keeping with the ratio of physicists to the total population, 1200 to 45 million in England. Hence the conclusion, "the physicist is about the scarcest of war materials." England has learned from her experience in World War I to guard her "scarcest of war materials."

Germany has had need of scientists—for example, Hertz, Röntgen, Haber. Yet the widow and daughters of Heinrich Hertz had to leave Germany for England after the self-appointed saviour of Germany obtained power. For the same reason, Haber, whose method of fixation of nitrogen saved Germany for a time in World War I, Nobel prize man in 1918, left Germany to die in exile.

Our own nation at times has had need of scientists. Recently the President appointed a committee to advise him in regard to the rubber situation, one James B. Conant, a chemist, one Karl T. Compton, a physicist, and an eminent man of affairs. The nation knew that the committee would be thorough in its investigation and unselfish in its conclusions. In both modern warfare and modern industry the applications of modern science are so extensive that they are beyond all prognostications of even a few years ago. We shall merely list some fields in which physics is predominant: aviation (the instrument board of an airliner contains about 40 instruments, all applications of physical principles); the motion picture industry; the thousand applications of the photoelectric cell; radio (there are 60,000,000 radio sets in American homes and many in the army, navy, air force); the cathode-ray oscillograph (a few years ago almost a rarity, now numbered in hundreds of thousands); the electron microscope, which extends the domain of the microscope by a factor of hundreds. The army, navy, air force, all are calling for physicists.

Millions of workers have found congenial and highly remunerative employment in the industries that have come into existence on account of discoveries made by workers in such fields as electric waves and electronics. Owing to such discoveries, hundreds of millions have enjoyed comfort and pleasure never before known. The millennium has been rapidly approaching. But now looking at the world, we see horror heaped on horror. Is science responsible for this descent into Hades? Certainly not; all that we can say is that nations which have made great advances in science may not necessarily have made a similar advance in wisdom.

Life is more than pure science, more than the application of science. In civilized society the life of one individual is dependent upon many others. In such a society there is no such thing as freedom of the individual. Scientists must give attention to problems involving the public. In a

recent editorial in *The Review of Scientific Instruments*, Professor Harnwell, Richtmyer's successor in the office of editor, urges a larger participation in politics on the part of the physicists.[4] In an excellent after-dinner address a year ago, Doctor Condon anticipated that editorial in discussing "A Physicist's Peace."[5] I propose to set forth briefly some views on topics that must engage our attention.

We are supposed to have a democratic form of government—one in which every citizen has an equal voice. That is very far from the truth. The fact is that we are governed to a considerable extent by pressure groups. Some time ago the President in a fireside chat told us that the standard of living of every citizen must be lowered. But we observe that this rule did not apply to labor unions. Their wages must be increased far beyond the increase in the cost of living. In two years subsequent to August 1939 the weekly earnings of employees in 25 of the chief manufacturing industries increased 46 percent. These higher wages helped to bring about an increase in the cost of living of about 20 percent. The income of a very large percentage of the nation's workers, of yours and mine, of individuals everywhere, not only did not increase, it decreased. There is no question about our standard of living. It has been lowered. Why then are labor unions exalted above the rest of the nation? The answer is easy. They form compact groups, often under the command of ambitious, selfish officers who take a very large money tribute from every member of their union. They stand ready to take advantage of any emergency in the life of the nation. They will hold up the nation. They will not only prevent the production of war or peace time goods, they will in some cases destroy property, even life, in order to gain their ends. The politicians are afraid of them. When the President said, "we have nothing to fear but fear itself," he might have added, "and back-stabbing politicians and certain pressure groups."

But the labor unions have some ground for their heartless, ruthless selfishness. They see officers of great corporations voting to themselves enormous salaries. They recall the case of the president of a great steel corporation during and after World War I who voted to himself what he euphemistically called a bonus of more than a million dollars a year for several years. Why was he able to do this? His company had "held up" the nation, forcing the government to pay huge amounts of money, yours and mine, for vessels which the nation needed. At the present time a magnate of the motion picture industry is diverting to his pockets $750,000 a year. He is cashing in on the work done in electronics, photography, acoustics—work done by many poorly paid scientists. Is it any wonder that labor leaders want to get for themselves and the army which they command part of the swag?

On account of the afore-mentioned facts and many others which cannot be here presented, I proposed during World War I and at various times since then this general principle—that averaged over a period of years there should be upper as well as lower limitations of income, that no officer of a company, no citizen, should be allowed to have an income more than ten times the average income of the adult wage earners of the nation. This is a proposal of enormous implications. It cannot be brought into operation at once. It would require a generation for its complete unfolding.

I know the arguments which are made against this proposal; "it is not the American way," "it would operate against initiative and incentive," "it would not make allowances for great minds." Suppose we were to give an American general a million dollars, would he go right out and smash Germany? Or if we gave it to a scientist, would he at once make a great discovery? Every great scientist of the past or present—Faraday, Röntgen, the Curies—can be quoted to the effect that great money rewards have no creative value.

Concerning labor unions, there is no objection whatever to them as deliberative bodies. But no man, no group of men except the national government in times of greatest emergency, should be allowed to prevent a competent worker from obtaining employment. Mass picketing should be prohibited; sabotage or mass violence should be regarded as criminal.

While the twentieth century scientist may not be able to cure all the faults of government, he should not give up in despair, as did Pierre Curie when, writing to the young woman who was to

[4] G. P. Harnwell, Rev. Sci. Inst. **13**, 313 (1942).
[5] E. U. Condon, Am. J. Phys. **10**, 96 (1942).

become his wife, he said, "we are powerless to change the social order." Pierre Curie after years of the most intensive work and of great accomplishment in science had a salary of $55 a month. He and Marie Sklodowska looked forward to a life of poverty. France had no need of scientists.

Physicists of America, we are citizens of no mean country. In many ways our nation stands at the very pinnacle. Our science, multiplying our power by a factor of 5000, has stepped up the muscular man power to at least 200 billion able-bodied men. Our mental operations have been greatly accelerated. We have machines that can solve certain problems in one hundredth of the time required by a mathematician using ordinary methods. The speed of communication, practically constant from the days of the Pharaohs to those of a century ago, has been so increased that now we can speak to all the people of the world and have our message transmitted with the speed of light. Our speed of travel has been so increased that we can send out an emissary to visit the chief nations of the world and have him return with his report in a couple of weeks. Many physicists can say as we survey these amazing accomplishments, "all of this I saw, part of this I was." Shall we then assert that we physicists are superior people, that we are above participating in the humdrum affairs of the world? We have seen what has happened to a great nation as a result of the proclamation of its superiority. We must recognize the fact that unless we take part in the affairs of the nation we may be governed by mobs armed with clubs.

We are now in the midst of a great war. But one of these days the Allies will close the score. The war will be over. But the war against ignorance, superstition, depravity, crime, control of our schools and colleges by medieval potentates is perennial. Richtmyer's life was largely devoted to furthering the participation of physicists in activities in the whole realm of physical science. His broad interests may serve as a model for what is now needed in a larger field. The nation has shown that it has need of scientists; we must show by vigorous participation in the perennial war that we have need of the nation.

The Development of Thinking as a Major Objective of College Physics Teaching

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THE social responsibility of college science teaching has been the subject of much speculation. There has been little fault found with the type or quantity of technical information that has been absorbed, more or less permanently, by physics students. Considerable criticism, however, both from within and without the teaching profession has been directed at the type of thinking done by science graduates. Many claims have been made that, outside of their own particular specialties, scientists show no better judgment in handling the ordinary problems of life than persons untrained in science.

The physical sciences, as Ruch and Orata[1] point out, should "develop the ability to use experimental methods in gathering and interpreting scientific data and in applying scientific facts and principles." The interpretation of data and the application of principles comprise the major phases of reflective thinking, which is the highest form of thinking of the type required in the solving of a problem. A *problem* is not the sort of exercise that may automatically be solved by the application of the correct formula, but is a more or less complex situation in which both the ultimate end and the details of procedure are obscure at the outset. Competence in reflective thinking is of particular importance in a truly democratic society, as the very existence of that society depends upon the thinking of its individual members in the cooperative solution of its problems.

[1] G. M. Ruch and P. T. Orata, "The nature of desired achievement in the school subjects," Rev. Ed. Research **9**, 522 (1939).

That the development of reflective thinking should be one of the normal outcomes of college physics teaching will undoubtedly be admitted by all physics teachers. The purpose of a recent study directed by the writer was to find what growth in the practice of reflective thinking took place during one semester of junior college physics, and to determine the probability that certain methods of instruction and elements of course organization are significantly related to the observed growth.[2] An original and carefully validated test of reflective thinking was administered at the beginning and at the end of the fall semester of 1940 to approximately 1000 students in six Southern California junior colleges. The test was found to have a reliability coefficient of .905 and was validated by ten indirect methods. One of the groups used in the validation consisted of analytical thinkers of proven ability, most of whom had never had any physics course. These particular men were selected because of their outstanding successes in analyzing the accounting and plant control technics of important industrial concerns and setting up procedures involving the use of punched card operated business machines. The high scores made by this technical group coupled with the absence of any direct relationship of test subject matter to materials taught in the physics classes provide an adequate basis for the claim that the test was not one of physics information but one of reflective thinking. All major calculations were made with the aid of Hollerith machines and were checked by 28 independent totallings of the data.

In the remainder of this paper questions will be raised that are answered by the findings of the study. Conclusions and recommendations based upon the findings will be presented with each question. Finally, specific suggestions will be offered which appear to have some merit in the development of reflective thinking on the part of physics students.

What growth in reflective thinking actually took place in the college physics classes? There was a mean growth in reflective thinking equal to 19.0 percent of the possible gain when all classes that participated in the study are considered. Other gains ranged from 10.23 to 27.54 percent for the various types of physics classes. These comparative percentage gains are presented in Table I, together with the mean initial scores, the mean final scores and the mean raw gains in test scores for the six types of classes investigated. It will be noted especially that while the engineering students were slightly higher in both initial and final mean scores than the other types of students, in neither raw gain nor percentage of possible gain are the engineering students superior. The mean score made by the previously mentioned analytical thinkers, who are in nonscientific work, was 50.0. This score in comparison with the initial value 40.1 for engineering students is taken to signify that the latter have not reached the maximum development in reflective thinking of which they are capable.

TABLE I. Summary of average initial scores, final scores, raw gains and percentages of possible gain made by six types of junior college physics classes on a test of reflective thinking.

Type of class	Initial score	Final score	Raw gain	Percentage of possible gain*
Engineering	40.1	47.7	7.6	19.5
Liberal Arts	39.7	46.7	7.0	21.9
Elementary	34.2	40.2	6.0	17.4
Survey	35.7	39.4	3.7	10.2
Applied	29.0	36.8	7.8	19.2
Transfer	29.5	41.6	12.1	27.5

* *The percentage of possible gain* for a particular type of course is the mean of the percentages of possible gain determined for each student individually. These individual values are the ratio of a student's raw gain to his possible gain.

What are some of the principal criterions by means of which growth in reflective thinking may be recognized and measured? The following criterions have been found which, if satisfied, are indicative of growth in reflective thinking:

(1) Recognition of simple truth or falsity.
(2) Recognition of a lack of sufficient data.
(3) Selection of the correct conclusion.
(4) Selection of reasons substantiating a conclusion.
(5) Rejection of false reasons.
(6) Rejection of irrelevant reasons.

These criterions provide a basis for the evaluation of instructional methods and course organization with regard to growth in reflective thinking.

[2] M. S. Allen, "An exploratory study of reflective thinking," unpublished doctoral thesis, University of Southern California (1942).

In the measurement of achievement what measure may be superior to that of raw gain made? The percentage of his possible gain which a student makes during a course appears to be more reliable in many ways as a measure of his actual achievement during the period of instruction than the raw gain that was made. Two faulty assumptions that are inherent in the use of raw gain as the measure of achievement are that of considering initial and final scores as independent variables, and of regarding either raw gains or total scores as of equal significance for all students. In the present study a correlation of .84 was found between initial and final test scores. The percentage of possible gain, which is found by dividing the raw gain in score made by a student by the gain that it was possible for him to make, avoids the afore-mentioned faulty assumptions and conforms more closely to normal growth curves when the test results are plotted.

Is the extent to which prerequisites are met related to growth in reflective thinking? The correlation coefficients found between growth in reflective thinking and the fulfillment of the prerequisites demanded for that same class indicate that the probability is better than 99 percent that meeting the prerequisites is followed by a corresponding gain in reflective thinking. However, when all the 1000 students are treated as a single group, a very low correlation is found between prerequisite meeting and growth in reflective thinking. The implication is that while setting prerequisites for a given course does select those students who can develop in reflective thinking with the methods used in a particular course, it does not necessarily follow that the prerequisites set up are the best ones or are even good. Whether the relationship would still be true under the problem approach as described in the conclusion of this paper is not known as yet. In view of indisputable evidence that the rigid plan of college entrance requirements is unjustified,[3] the thoughtful instructor should consider with great care the prerequisites that he sets up for his courses.

Is intelligence, as measured by the Thurstone test, related to growth in reflective thinking? The intelligence of students, as expressed in terms of their Thurstone scores, yielded a correlation coefficient of .68 with initial scores on the test of reflective thinking, and a coefficient of .70 with final scores. However, when raw gain in test scores was correlated with Thurstone scores, the coefficient was −.23. The correlation of Thurstone scores with percentage of possible gain yielded a coefficient of −.14. Because of the large number of students involved in the study, both of these negative coefficients express to a degree of certainty of better than 99 percent that the mere possession of a high intelligence will not result in a corresponding growth in reflective thinking. It seems very evident that this lack of any positive relationship between intelligence and growth in reflective thinking calls for an immediate and extensive evaluation of teaching procedures. The various instructional methods commonly employed by college physics teachers might well be critically examined to ascertain the frequency with which students are faced with novel situations that must be thought through in order for them to proceed. If intelligence is considered to be not only the ability but the will to decide rightly, then the need for wide experience in the practice of deciding rightly becomes obvious. The results of this study indicate that the selection of relevant data from a large amount of available material and the recognition of a lack of data should especially be stressed.

Are the principal methods of teaching employed in college physics classes related to growth in reflective thinking? Methods of instruction vary greatly in their relationship to growth in reflective thinking. The only methods that showed a positive relationship to growth in reflective thinking were the use of references outside of the basic textbook and the preparation of written reports. Some of the most frequently used instructional methods, such as lecture-demonstrations and a strong emphasis on mathematics, were found to bear a negative relationship to growth in reflective thinking. This rather strongly substantiated finding is not to be taken as implying that lecture-demonstrations and a strong mathematical emphasis do not have much justification even as at present presented, nor that these two elements of instructional method

[3] D. Chamberlin, E. Chamberlin, N. E. Drought and W. E. Scott, *Adventure in Education Series*, Vol. IV, "Did they succeed in college?" (Harper Brothers, 1942).

might not be so changed as to retain all of their present values and, in addition, be positively related to growth in reflective thinking. The existence of so many variables related to growth in reflective thinking was recognized in the organization of the present study. No claim is made for the establishment of the nature or the strength of cause-and-effect relationships; this must await subsequent controlled experiments. Substantial evidence has been accumulated, however, in support of the conclusion that the chance is less than one in a hundred that there is a positive relationship between growth in reflective thinking and lecture-demonstrations or mathematical emphasis. It is the belief of the writer, so far not objectively verified, that the usual plan of using a lecture-demonstration for the purpose of illustrating a principle, instead of for the solution of a problem that is novel to the students, is largely responsible for this serious lack of relationship. The absence of significant relationship of mathematics to growth in reflective thinking may possibly be attributed to the customary teaching of mathematics as a "pure" subject, which seems to mean isolation from reality and application. A fresh set of physics problems to accompany the textbook and having their origin in some vital life situation wherein mathematics is seen as a necessary and helpful tool might do much to strengthen the relationship of mathematical emphasis to growth in reflective thinking.

Is the plan of course organization as used related to growth in reflective thinking? Those courses for which instructors claimed a plan of organization that recognized the individual differences of the students, and those courses in which individual conferences were scheduled with students, alone showed large enough growth in reflective thinking so that a significant and positive relationship may be claimed. Flexibility of organization and method of grading were among the elements found unrelated to growth in reflective thinking.

Conclusion: Suggestions based upon the findings of the study herein reported do not deal primarily with subject matter, methods and course organization. These are not of the major importance in themselves. First emphasis is placed upon the urgent need for related and worthwhile problems as the basis for course work. Many advantages are to be derived from the use of a relatively small number of broad problem areas rather than a large number of independent and limited specific problems. Examples of the latter type of problem intended to stimulate reflective thinking are, "How would you construct a slow-acting relay," or "How would you protect a dry cleaning establishment from electrostatic explosions?" The use of a multiplicity of independent problems of this type, while very effective in many respects, presents serious difficulties in the library because of the wide range of technical magazines and books that must be available. In addition, there is an undesirable lack of continuity resulting from the use of these many unrelated problems.

A compromise of the afore-mentioned plan, as now used by the writer in lower division courses, avoids the difficulties just mentioned. The specific problems which are used as the basis for discussion, for mathematical exercises and for laboratory work are drawn from but six problem areas. This provides the continuity needed for effective course planning and also a rich understanding of six areas of living that are vital in war and peace. These problem areas are as follows:

(1) The air-conditioning of an office building containing stores, offices and a theater.
(2) The extraction, processing and transmission of petroleum products from oil well to ultimate consumer.
(3) Electric and gas welding.
(4) The operation and design of steam, gasoline and Diesel engines.
(5) The design, construction, flight and navigation of airplanes.
(6) The generation and transmission of electric energy.

Any principle of physics for any type of student may thus be presented in a meaningful situation drawn from one of these six problem areas. Many other similar problem areas may of course be used, but these six were selected because of their universal importance, general interest and breadth of coverage of standard physics subject matter. As the elements necessary to develop reflective thinking are called for only when the student is confronted with a worthwhile problem, the proper selection of problem situations may well be the basis for all lower division physics curriculums.

Experiments with Vapor Pressures

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BOYLE'S LAW WITH CONDENSABLE GAS

As a variation from the conventional experiment, butane may be substituted for air in the Boyle's law apparatus. The low-test "bottled gas" used for rural gas stoves is a mixture of butane (boiling point, 0°C) and isobutane (boiling point, −10°C).[1] About 100 cm^3 of the liquid is sufficient; it may be obtained in an open bottle from the local dealer. After it has boiled away for a short while, the boiling point rises to −5°C or higher and the residue is then largely normal butane. This is introduced into the Boyle's law apparatus.

When the experiment is performed at room temperature, Boyle's law is found to hold nearly as well as it does with air. The pressure required for condensation at 20°C is about 3 atmos., which is outside the pressure range usually employed. But at a lower temperature, which may be obtained by surrounding the apparatus with ice water or, more simply, by performing the experiment outdoors in winter time, the gas liquefies during the experiment with—to the student—a surprising break in the curve. The condensation will not occur at exactly constant pressure because the gas is a mixture of isotopes and, when a temperature bath is not used, because of temperature variation due to the heat of evaporation.

The liquid remaining after the apparatus has been filled may be enclosed in a stoppered bottle to show the liquid at room temperature, illustrating what one would see in a tank of carbon dioxide if it were transparent. A strong bottle—for example, a mercury container—should be used. I have never known such a bottle to break in this use, but for safety it may be armored with chicken wire.

For effective demonstration of the distinction between gases and vapors, one may make a substantial U-tube, each arm being 70 cm long and preferably about 1 cm^2 in cross section; each arm of the U-tube is closed at the top, and an inlet tube is attached to the bottom bend. A small-bore rubber tube 2 m long connects the inlet tube to a leveling bulb. This tube should be wired to the glassware and over part of its length reinforced by friction tape so that it will withstand a pressure of 3 atmos. The U-tube is wired securely to two edges of an abbreviated meter stick (the volume scale) and is placed inside a large glass tube which will contain the temperature bath. A stopper at the bottom of the large tube has a central hole for the inlet tube to the U-tube and another hole for a drain; the tube is firmly wired to the stopper so that the apparatus may be inverted for filling. The scale should be painted over with Glyptal for protection against water. The whole apparatus is mounted on a tall iron stand with provision for mounting another meter stick to measure heights above the tops of the U-tube.

The U-tube is now filled with mercury and then this is displaced for about 50 cm with air in one arm and to the same height with butane in the other. The air can be worked through the mercury in the rubber tube and, by tipping the apparatus, into the proper arm of the U-tube. The U-tube must be well supported by the meter stick in the larger tube to avoid breaking when the heavy mercury column is tipped. The liquid butane is poured into the leveling bulb; the vapor first drives the air out of the bulb and is then passed into the U-tube in the same way as the air. If there is a small excess of butane it may be spilled over into the air chamber.[2] If convenient, each arm may be filled so that the mercury levels will be at the 22.4- or 44.8-cm^3 mark under standard conditions—that is, filled with exactly 1 or 2 millimoles of gas; a stripe may then be painted at this level to allow emphasis on Avogadro's law.

[1] This is the low-test gas; the "super" gas for winter use is propane, which is not suited for this experiment. Butane is a raw material in artificial rubber production, but (at the time of writing) this low-test gas is being sold. Butane has the advantage of availability and does not react with mercury. Phosgene has a somewhat higher boiling point (8°C) and probably would be preferable.

[2] Since the filling is a little troublesome, the demonstrator may prefer to equip the apparatus with stopcocks at the top of the U-tube. The construction suggested in the text is for a permanent demonstration piece.

When the leveling bulb is raised at room temperature, the two mercury columns begin to rise almost together, though even now the butane is slightly more compressible than the air, showing the limitation of Boyle's law. Condensation begins when the bulb is raised about 2 m. The remarkable phenomena of condensation are shown to better advantage when the temperature is lowered somewhat; the mercury level rises in the butane tube at a nearly constant distance below the leveling flask while the other column remains behind.

SIMPLE EXPERIMENTS ON PARTIAL PRESSURE

The concept of partial pressure and Dalton's law, largely ignored in the elementary physics course, are quite important for chemistry, biology and premedical students. Dalton's law is assumed in the usual treatment of humidity, but its significance can be shown more directly by several simple experiments.

The fundamental fact of the addition of pressures is shown by a familiar experiment. If a little ether is poured into a reagent bottle and the glass stopper quickly but loosely inserted, the stopper will pop up and down for some time as the ether adds its partial pressure to those of the nitrogen and the oxygen in the air.

The Charles' law experiment has probably been performed in the lecture room or laboratory, the increase in air pressure with temperature being measured in the range up to 100°C with the aid of the ordinary bulb-and-mercury column, gas-thermometer type of apparatus. The experiment should be repeated with a few drops of water in the bulb. The neck of the bulb, outside the heating bath, must be heated to prevent condensation of water. Of course, the pressure curve now is very different from the Charles' law curve; the differences in the ordinates of the two curves give the vapor pressures of water.

The student should now be able to analyze the performance of the common glass coffee-maker in which the water is forced from a lower vessel into the coffee in an upper vessel by vapor pressure. The student should measure the temperature at which the water rises to the upper vessel and *appears* to boil. Of course, if the lower vessel is completely filled, this occurs at the boiling point (under the slight hydrostatic head). But if the lower vessel is half filled, as in ordinary use, this occurs at about 80°C. Air is then gradually bubbled out of the lower vessel, and the temperature there rises to the boiling point. The air having been exhausted, the rising steam bubbles can no longer pass through the 80° water in the upper vessel. These bubbles condense until the heat of condensation raises the temperature of this water to the boiling point; only then can they reach the surface. This simple experiment involves several physical principles. When the apparent boiling begins, the volume of the air in the lower vessel is (say) doubled, the partial pressure of the air has been reduced to half (by Boyle's law), or, more exactly, to a little more than half (because of Charles' law) and the rest of the pressure is the partial pressure of the water vapor. As a check, the vapor pressure of water for the observed temperature should be obtained from a table.

A Simple Impact Experiment

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IMPACT experiments, as described in most laboratory manuals, are not simple enough to attract the beginner in physics. This article describes an experiment which is simple and interesting, and which gives reasonably good results. It may be used either as a laboratory exercise or as a demonstration by the teacher.

Briefly, a mass is dropped into a scalepan suspended by a spiral spring (Fig. 1) and the resulting "throw" is observed. From this throw, the stiffness factor of the spring and the period of oscillation after dropping the mass, it is possible to calculate the initial velocity of the scalepan, which is the velocity after impact of

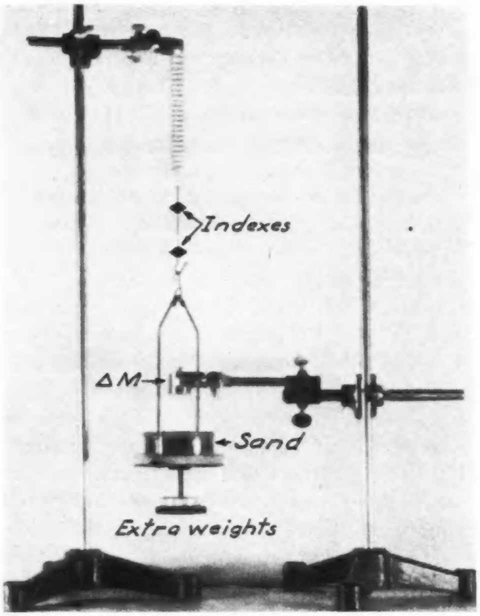

FIG. 1. Apparatus for impact experiment.

the dropped mass. The motion is linear, and thus any reading of angles or computation of moments of inertia is avoided.

A spiral spring must be chosen that elongates by equal amounts for equal increments of load. It should be light and fairly stiff, and the square of the oscillation period should be proportional to the load. About 12 turns of a spring taken from an old shade roller serves admirably.

In order to observe the movements of the scalepan, the experiment may be carried out in the field of a projection lantern. Between the spring and the scalepan there may be a stout wire to which are affixed two lumps of metal, each turned to a sharp V-edge, to serve as indexes. The indexes should not be so close together as to cause confusion, but should be separated by a distance nearly equal to the diameter of the condenser lenses. The image of the indexes falls on a screen carrying any convenient scale; the scale is calibrated by comparing the distance apart of the images, measured in scale divisions, with the actual distance apart of the indexes. If only one student is working on the apparatus, it will be found convenient to employ a translucent scale near the lantern and to fold back the projection beam on this scale by means of a plane mirror; the student can release the weight to be dropped and be near enough to read the scale easily. If the experiment is performed as a demonstration, one can employ an erecting prism, turning the latter about the optic axis through an angle of 45°. The image now moves horizontally, and the scale of the lecture galvanometer can be employed.

Let M_0 be the combined mass of scalepan and index rod. In order that the throw of this mass may occur slowly enough for the scale to be read with ease, the mass should be fairly large and it may be necessary to add some weights to the scalepan; their mass is included in M_0. (See "Extra weights," Fig. 1.) Let the mass to be dropped be ΔM, and let the sum $M_0+\Delta M$ be designated by M. If ΔM falls through a distance H, its velocity v immediately preceding impact is $(2gH)^{\frac{1}{2}}$. Now if ΔM is allowed to fall into a dish of sand, the impact is practically inelastic and the velocity V immediately after impact is

$$V=\frac{\Delta M\cdot v}{M_0+\Delta M}=\frac{\Delta M}{M}(2gH)^{\frac{1}{2}}. \tag{1}$$

The support carrying the spring is so arranged in height that one of the indexes just appears in the field of the lantern; its actual position may be called P. The mass ΔM is now placed in the scalepan, and the resulting rest point of the same index may be called O. Let $PO=a$. If ΔM is now placed in the clamp at a height H above the center of the sand and is allowed to fall, the index moves to a point Q. Let $OQ=A$. The actual distances a and A are deduced from the scale readings corresponding to P, O and Q, and the calibration of the scale. After the dropping of ΔM, the index performs simple harmonic motion of amplitude A, above and below O. The velocity at P is to the velocity at O in the ratio PS/OS (Fig. 2). Hence

$$V=\frac{2\pi A}{T}\,\frac{(A^2-a^2)^{\frac{1}{2}}}{A}=\frac{2\pi}{T}(A^2-a^2)^{\frac{1}{2}}. \tag{2}$$

If the velocity V as computed from this equation agrees with the value as computed from Eq. (1), we have proved that the sum of the momenta is the same before as after impact.

Since $(T/2\pi)^2 = M/k$, k being the force constant for the spring, Eq. (2) can be transformed into the familiar energy equation,

$$\tfrac{1}{2}MV^2 + \tfrac{1}{2}ka^2 = \tfrac{1}{2}kA^2, \qquad (3)$$

stating that the total energy at P is the same as that at Q. Substitution of known values for the various quantities may be an interesting exercise for a student.

If the expression $\int Fdt$ for the impulse of the spring is integrated from P to Q, the result is found to be the momentum MV.

If the impact of ΔM on M_0 were perfectly elastic, M_0 would rebound with a velocity $2\Delta M/M$, which is double the velocity V for the inelastic case previously considered.

The experiment throws light on some everyday experiences. It will also serve to explain to the student why, in finding Young's modulus for a wire, he is warned to put successive increments of load in place gently. If a wire is already loaded to near its elastic limit, it may stand an additional stretch a if the corresponding additional load is not allowed to fall into place. But if the load is allowed to fall through a height of even an inch, it might call for a total movement $a+A$ sufficient to break the wire.

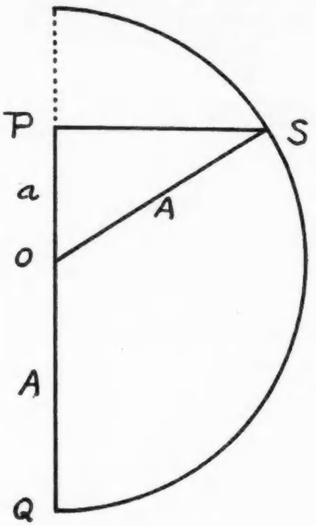

FIG. 2.

Fellowship of Sigma Delta Epsilon, Graduate Women's Scientific Fraternity

WOMEN with the equivalent of a Master's degree, conducting research in the mathematical, physical or biological sciences, who need financial assistance to complete their work for the doctorate and who give evidence of high ability and promise, are eligible for the $1000 Sigma Delta Epsilon fellowship. The appointee must devote the major part of her time to the approved research project, and not engage in other work for remuneration unless such work shall have received the written approval of the Fellowship Board. Application blanks may be secured from Dr. Eloise Gerry, U. S. Forest Products Laboratory, Madison, Wis. Applications and reference statements, both in triplicate, must be submitted before March 1, 1943. Announcement of the award will be made early in April.

A Stroboscope for the Demonstration of Phase Differences in Alternating-Current Circuits

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THE phase relationships of alternating currents are especially difficult to present to students of general physics. For the most part the students have not the necessary background to make the mathematical approach effective nor do they have, in general, much previous experience of a practical nature to aid them. Although a number of good and striking lecture experiments[1,2] are usually given which should be of great help, too often the student merely observes and leaves the lecture with no real understanding.

At the University of Oregon we have supplemented the lecture-demonstrations with an alternating current experiment. This experiment is built around a 60-cycle sec^{-1} stroboscope[3] which is permenantly mounted in the laboratory. This model and two portable models are described below.

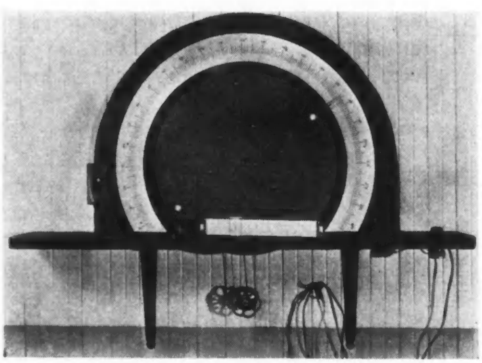

FIG. 1. Front view of the stationary model.

[1] Sutton, *et al.*, *Demonstration experiments in physics* (McGraw-Hill), **E228–E269**, pp. 344–366.

[2] N. H. Black, "Lecture demonstrations in elementary physics," Am. J. Phys. (Am. Phys. T.) **2**, 91–94 (1934), esp. p. 93.

[3] The design here presented represents several improvements over a similar design first seen at the University of Iowa.

THE STROBOSCOPE

An alternating current, 60-cycle sec^{-1}, 1800-rev min^{-1} synchronous motor is mounted in a recess in one of the laboratory walls (Fig. 1). This arrangement is convenient in our case but is not necessary; the whole apparatus might well be located within the room or made portable. A fiber board disk A (Fig. 2) is attached to the motor axle. This disk, 25 cm in radius, has two holes 2 cm in diameter placed diametrically opposite each other at distances of 22 cm from the center. With the motor in rotation one or the other of these holes passes a given point 60 times per second. Behind the disk and mounted on a collar placed about the motor axle but not attached to it is an arm B made of brass tubing which supports a neon light socket C and a pointer D. This arm is rotated by a cord belt drive E extending from the collar to a small hand-rotated wheel F which can also be seen below the apparatus in Fig. 1. One end of a lamp cord long enough to reach the apparatus upon which it is desired to make measurements is connected to the neon light socket C and extends down the brass tubing of the arm B to a point near the axle. On the other end of the lamp cord are two radio prods for connectors. A 10,000-ohm current-limiting resistor is inserted in one of these leads. A 1-w neon bulb with a cylindrical center electrode and a spiral of wire surrounding it for the second electrode is used. As seen in Fig. 1, a scale marked in degrees is placed parallel to and slightly back of the rotating disk. In this position the scale serves as a protective device to prevent contact with the rotating disk. The pointer D attached to the neon light is immediately in front of the scale.

To use the apparatus for the determination of phase difference one needs to know the voltages, V_a and V_b, at which the neon light goes on and off as illustrated in Fig. 3(a). These voltages may be determined by a simple direct-current

potentiometer circuit with a voltmeter across the light and a reversing switch to change the polarity. These voltages differ slightly, depending

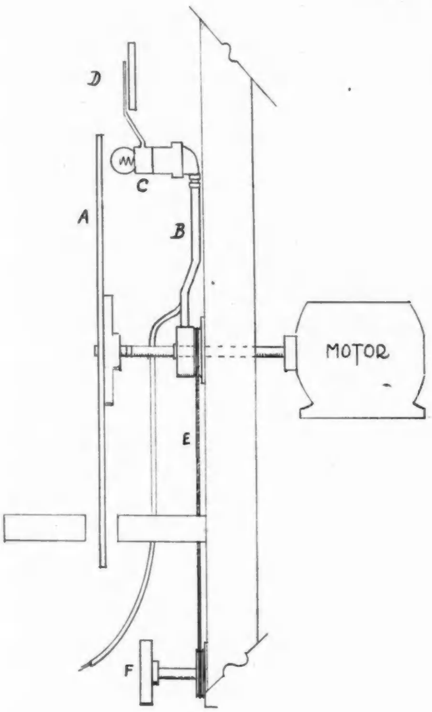

FIG. 2. Cross-sectional view of the stationary model.

upon the kind of neon light used. When the stroboscope is put into operation by closing the motor switch and connecting the neon bulb to an a.c. voltage, the student observes with some astonishment that as the neon bulb is rotated by the hand wheel F (Fig. 1) away from the zero position at the left, first only one electrode glows, then the light apparently disappears, next the other electrode glows, after which the light again disappears and finally the first electrode glows. The positions at which the light changes, corresponding to t_1, t_2, t_3 and t_4, Fig. 3(a), are easily read on the scale surrounding the rotating disk. Now, suppose we have two voltages that differ in phase by x electrical degrees; then the aforedescribed phenomenon repeats but is shifted $x/2$ mechanical degrees. If the speed of the motor were 60 rev sec^{-1} the shift would be equal to the phase difference, but since the speed is 30-rev sec^{-1}, the number of mechanical degrees is equal to one-half the number of electrical degrees.

If the peak voltage V_m (Fig. 3) is not known from other experimental data, the apparatus itself may be used to determine this value with sufficient accuracy for the sketching of the sinusoidal curves. The angle ϕ [Fig. 3(a)] in electrical degrees is determined by reading the stroboscope and multiplying by 2; then θ is found by interpolation. Next V_m is found by solving the equation, $V_a = V_m \sin\theta$ [see Fig. 3(b)].

Two other designs have been constructed. The first[4] utilized a washing machine motor with four slots machined in the motor[5] to make it run at synchronous speed. This proved satisfactory except that occasionally the motor would slip out of synchronism. The second design[6] is shown in Fig. 4. The cost of this model is kept small by using parts that are commercially available. The wheel which is nearest the motor and rotates at 1800 rev min^{-1} contains two small holes about 1 in. in diameter, diametrically opposite each other and at the same distance from the axis as the neon bulb. The wheel carrying the neon bulb is turned slowly by hand. On this latter wheel is

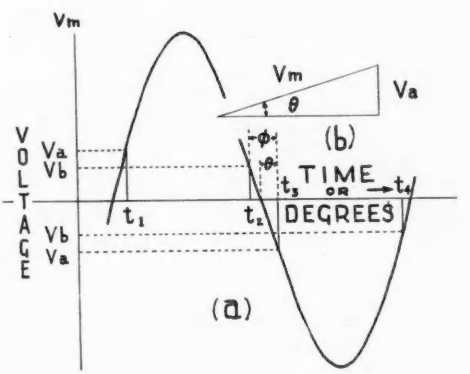

FIG. 3. (a) Sine curve illustrating the voltages at which the neon light goes on and off. (b) Vector triangle.

[4] Made at Parsons College, Fairfield, Ia.
[5] C. B. Brown, "An easily constructed synchronous motor," Rev. Sci. Inst. **4**, 295–296 (1933).
[6] Made at Albany College, Portland, Ore.

a compass card marked in degrees. A string extending from a collar about the axis through a small hole in the base of the instrument serves as fiduciary marker. It is kept taut by a small

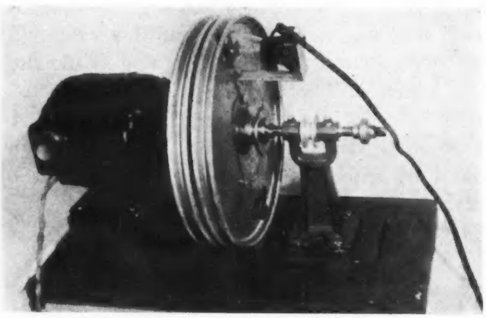

FIG. 4. Portable model.

spring underneath the assembly. The smooth rim of the high speed wheel minimizes any danger to the students should they accidentally come in contact with it.

The cost of construction of any of these models is about thirty dollars exclusive of the price of the motor.

THE ALTERNATING-CURRENT EXPERIMENT

The alternating-current experiment carried out with the stroboscope first described is sufficiently novel to merit a brief description. It has been found most satisfactory when conducted as a laboratory demonstration, with one instructor supervising a group of 10 or 12 students, making the necessary explanations and aiding in the taking of data. The experiment consists of two parts. In part one, which does not utilize the stroboscope but will be briefly described, the power relationship $P=VI\cos\theta$ is assumed; P, V and I being measured by a wattmeter, voltmeter and ammeter, respectively. The student is required to calculate θ and then draw for the report the sinusoidal curves showing the proper phase relationship between the voltage and current curves.

In part two, series resonance is investigated. An ammeter, a fixed inductor, a variable resistor and a capacitor variable in steps are connected in series to an alternating 60-cycle $\sec^{-1}$ source. Data are obtained from which the student later plots the typical current-capacitance resonance curve. The experiment is completed by demonstrating with the stroboscope the phase relationship existing between the voltage across the resistor, inductor and capacitor at resonance. Sufficient data are obtained to make it possible for the student to plot the three sinusoidal voltage curves superimposed on one graph. The students almost universally comment that this is one of the hardest but most instructive experiments of the group that we present.

The writer wishes to thank Mr. H. D. Osburn, who aided materially in the construction of the University of Oregon model.

TODAY the arts and sciences have become separated, to the detriment of both. Five hundred years ago this was not so: men of outstanding ability expressed themselves in the language of art, but thought deeply, accurately and long in the manner of science. This produced a symbolism at once romantic and yet disciplined. It may be one of the tasks of physics to help recapture this in our own time.—F. I. G. RAWLINS, *J. Sci. Inst.* **19**, 22 (1942).

On the Preparation and Certification of Teachers of Secondary School Science*

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RECOGNITION of the fact that the preparation of school science and mathematics teachers is not adequate prompted the American Association of Physics Teachers some time ago to appoint a committee for the study of the problem of secondary school science teaching in cooperation with other scientific societies.[1] This move finally led to the formation of the Cooperative Committee on Science Teaching[2] sponsored by the American Association of Physics Teachers, the American Chemical Society, the Mathematical Association of America, the Union of Biological Societies and the National Association for Research in Science Teaching.

The first problem considered by the committee was the teacher training program as it is reflected in the certification laws set up by the various state departments of public instruction and as it appears as a major responsibility of the institutions of higher learning, where students are prepared for the teaching profession. Progress in teacher education and state requirements for certification are intimately related. Therefore, a study of the present certification laws has been made. Possible modifications have been worked out, leading to recommendations as regards teacher training programs which are practical and would assure us that the prospective secondary school teacher is well prepared for his job.

The problem lies primarily with the smaller schools. In the larger schools the better economic situation of the teacher, more adequate equipment and larger number of students in the science courses serve to attract well-trained personnel. In the small school one and the same teacher has to divide his attention among a great many unrelated tasks.

As a consequence certification requirements for the science and mathematics teachers are very low. The North Central Association of Colleges and Secondary Schools considers "science" as a single subject field and requires only 15 semester hours of preparation, the same number of hours as required for English, for history and for mathematics. The 15 hours distributed over several sciences provide little or no preparation in any one of them. The small number of hours required for the whole field of the sciences makes it possible for the prospective science teacher to obtain simultaneous certification in other, unrelated, fields, and we find all sorts of chaotic teaching combinations which cannot be justified by the background of the teacher or the real needs of the school.[3]

Studies made of teacher assignment practices[4] in the secondary schools of the North Central Association show that 53 percent of the science teachers were teaching two subject fields, 17 percent were teaching three fields and 2 percent, four or more fields. Since a "subject field" is a group of related subjects, science as a subject field includes physics, chemistry, biology, earth science and general science, and we find many teachers teaching all these subjects and others besides. Contrast this with the assignments of agricultural teachers, 71 percent of whom are teaching one subject only!

These conditions, varying in different sections of the country, could be eliminated if certification standards were raised and made uniform. Various committees have studied teacher certification, and all of them agree that reciprocity between states as regards teacher certification should be established. This is possible only if certification requirements in the various states are more uniform than they are now. It is also

* A preliminary report of the Cooperative Committee on Science Teaching. Reprints may be obtained from Prof. R. J. Havighurst, Chairman, University of Chicago, Chicago, Ill.

[1] K. Lark-Horovitz, Am. J. Phys. **10**, 60 (1942).

[2] G. W. Warner, Am. J. Phys. **10**, 121 (1942).

[3] E. I. Potthoff, "Simplifying the combination of subjects assigned to high school teachers." Univ. of Ill. Bull. vol. 36, No. 87, 1939.

[4] R. F. Evans, "A study of teacher assignment practices in secondary schools of the North Central Association." North Central Assoc. Quarterly **16**, 271–91 (1942).

desirable that the teacher's certificate be valid for a limited period only, that recertification be based on definite professional improvement and that the certificate be given for related fields primarily.

The Committee recommends a policy of certification in closely related subjects within the broad area of the sciences and mathematics; more specifically, in any three of the following five subjects: (i) biological science, (ii) chemistry, (iii) earth science, (iv) mathematics and (v) physics. "For certification in three subjects the Committee recommends that a total of at least 60 semester hours credit be required in this area, with at least 18 hours credit in each subject for which certification is granted, except that 24 hours credit should be the minimum for certification in biology, including courses in both botany and zoology."

Since these are minimum requirements, a teacher should be urged to take further work in the science in which he wishes to specialize. The Committee also approves a policy of certification of science teachers in one additional nonscience subject. It also approves of certification of teachers with major preparation in other areas for one field of science. This is necessary to meet the needs of the small schools, but in this case the minimum number of science hours required for certification shall be not 18, but 21 to 24 hours.

Can such a certification policy be effected by teacher training programs in the universities and colleges? Questionaries sent recently by the Committee to some 200 institutions of higher learning in various parts of the country have received about 50 percent response. Of these 100 institutions, 31 have set up special programs for the preparation of science teachers. In most cases the program has been worked out by the various science departments in cooperation, or by collaboration between the science and education departments, so as to obtain information on actual teaching assignments to be expected by the future teacher. The results of the inquiry indicate that universities and teachers colleges make more adaptations for special science teaching programs in the departmental curriculums than do the liberal arts colleges.

To improve the preparation of secondary school teachers it seems necessary that training institutions should come to regard the teacher training program as professional in character, as are programs for preparation in medicine, engineering, law and other professions. There should be a section in the college catalog devoted to the program for the preparation of science teachers. Such a program worked out by collaboration between the science and education departments will provide teachers with a sufficient background of general education and adequate mastery of the subjects to be taught.

It may be desirable to require 10 to 15 semester hours of work beyond the normal four-year undergraduate program to prepare a teacher, but even the minimum of 120 semester hours for graduation should allow for an adequate number of hours to prepare the future science teacher. If one-half of the ordinary curriculum of 120 hours is devoted to courses in the sciences, then 24 hours can be assigned to a major field and 18 hours each to two other sciences. Such an arrangement leaves a reasonable amount of time for the general education requirement and also allows for one minor in an unrelated field, so as to prepare the prospective teacher for the needs of the small school and his first teaching assignment. Current opinions on teaching assignments seem to support such a program since it will allow assignment of beginning teachers more nearly to fields for which they are best prepared.

The Committee's recommendations can only be realized by the concerted action of the college faculties preparing the teacher and the state department setting certification standards. Recent developments arising from the urge to meet the war situation show that such cooperation may effectively correct present shortcomings. The continued cooperation among scientific societies, college faculties and state departments may well lead to a better understanding of the problem of science teaching in the schools and to its solution.

NOTES AND DISCUSSION

A Modified Rowland Ring Experiment

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THE Rowland ring method of measuring hysteresis has the disadvantage, as has been pointed out before in this journal,[1] that it is quite easy to make mistakes in the sequence of operations which must be carried out. When one mistake has been made it is necessary to start the measurements afresh, and much time may be lost. As an experiment for an undergraduate electricity and magnetism laboratory the Rowland ring method in its usual form is, therefore, rather unsatisfactory. A student is apt to spend an inordinately long time repeating measurements before he successfully completes a hysteresis cycle, if, in fact, he is able to do so before the apparatus is needed by another.

A simple modification of the Rowland ring method, suitable as an experiment for undergraduates to illustrate hysteresis and magnetic-circuit theory, reduces the likelihood of making mistakes and has been found to serve satisfactorily. Instead of using a continuous ferromagnetic ring, one with a thin transverse cut is wound with an appropriate number of turns of wire. The air gap is made just wide enough so that a thin search coil may be inserted into it and withdrawn. This search coil takes the place of the secondary winding used in the usual Rowland ring experiment.

In carrying out a hystersis cycle with the apparatus described here the magnetizing current may be conveniently changed by means of a potential divider and a series rheostat. In order to avoid making a mistake one need only remember in which direction the sliders should be moved when in the four different quadrants of the hysteresis cycle. The current may be changed slowly and, in case a mistake in direction is made, it is apt to be so small that the shape of the hysteresis loop is only slightly changed and the student may proceed further without seriously altering his results. On the other hand, in the usual Rowland ring experiment, any mistake made is apt to be so large that the hysteresis cycle must be started all over again.

The apparatus consists of a cast-iron ring having a mean diameter of 10.8 cm and a mean cross-sectional area of 2.61 cm^2, which is also the area of the air gap. The air gap is $\frac{1}{8}$ in. long. The ring is wound with 2290 turns of No. 28 cotton-covered copper wire. A current of 0.6 amp, which can be passed through this winding without overheating it, is enough to produce an approach to saturation.

Owing to the fringing of the lines of force at the air gap the search coil should have an area considerably larger than that of the cross-sectional area of the gap, in order to make sure that almost all the lines are cut by the search coil when it is moved into or out of the gap.

[1] W. H. Eller, Am. J. Phys. **8**, 234 (1940).

Experiments with a Condenser

Rogers D. Rusk
Mount Holyoke College, South Hadley, Massachusetts

TEACHERS of beginning physics who have experienced the kind of hot, humid weather which was encountered by the writer while teaching electrostatics last summer know how flatly experiments in the subject may fail.

When ebonite rods and Wimshurst machines refuse to behave properly the charge and discharge of a condenser may still be strikingly illustrated by connecting one or two 4-μf high voltage condensers of the Pyranol type across the secondary terminals of a 1500- or 2000-volt neon sign transformer in series with a No. 879 rectifier tube which may be operated from a separate filament transformer. Pressing a key for a few moments in the primary circuit of the transformer, the circuit being connected to the 110-volt a.c. circuit, allows the rectifier to heat up and the condenser to charge. After the key is released, two short bare wires projecting beyond the terminals of the condenser may be pushed together with a stick or insulated handle, and the spark that follows both looks and sounds impressive.

This apparatus can give a serious shock, and due caution should be observed. The various pieces may be permanently mounted on a wooden base to provide a convenient source of high potential for a number of experiments. Of course, the idea may be generalized to include additional condensers and one or more voltage doublers, with many obvious possibilities for demonstration.

An experiment which is not new but which may have been overlooked by many demonstrators is that of exploding small wires in the spark gap. An inch or two of No. 36 copper wire may be exploded with greatly increased effect. This is, of course, a momentary source of the highest obtainable temperatures and of high temperature spectra. The spectrum observed is usually an absorption spectrum, the characteristic lines of the substance exploded being absorbed from the continuous flash background. The wire to be exploded may be illuminated by a small spotlight and an image formed on a screen with a reading glass. This enables a large class to see that the wire is there before the explosion and is not there afterward. Other useful experiments will doubtless suggest themselves to those setting up the apparatus.

An Electronic Impulse Timer

C. W. Sheppard
South Dakota School of Mines, Rapid City, South Dakota

IN connection with acceleration experiments in a small physics laboratory, a moderate budget made it desirable to supplement the excellent commercial spark timer already being used with an additional, less expensive, instrument.

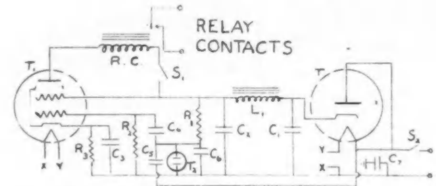

FIG. 1. Circuit diagram: C_1, C_2, 8-μf electrolytic; C_3, 25-v, 25-μf electrolytic; C_4, 0.02-μf; C_5, 0.005-μf; C_6 uncertain (0.03-μf for 30 cycle/sec. in one case); C_7, 0.05-μf; R_1, 2 megohms; R_2, 0.5 megohm; R_3, 500 ohms; L_1, 15-h filter choke; T_1, 117L7; T_2, $\frac{1}{4}$-w neon lamp; *R.C.*, 2500-ohm relay coil.

An electronic timer was developed which consists of parts obtained from a radio supply house and which is easily constructed with simple tools.

The circuit is shown in Fig. 1. *R. C.* is the coil of a small, low-cost relay,[1] having a 2500-ohm winding, of the type sometimes used in photo-cell work. This relay was connected into the plate circuit of a power tube whose grid was controlled by a small $\frac{1}{4}$-w neon-tube sawtooth oscillator. The relay contacts are placed in the circuit which is to be periodically broken. The principle of the oscillator involves the charging of the condenser C_6 through the resistance R_1 until the striking potential of the neon tube T_2 is reached, whereupon the condenser discharges through the tube. The discharge ceases when the extinguishing potential of the tube is reached, and a new cycle is initiated. The frequency depends upon the capacitance of C_6, the resistance of R_1, and the difference between the striking and extinguishing potentials of T_2. It is to be noted that in itself this oscillator would not have a dependable frequency, owing to the many drifts which can beset such circuits. Stability against moderate variations is achieved by coupling the circuit to the 110-v alternating current line through the small condenser C_5. By adjusting the time constant of the oscillator the circuit can be made to lock in at a submultiple of 60 cycle/sec down to at least 15 cycle/sec.

The tube which was chosen—T_1 in Fig. 1—was the RCA 117L7. This tube has the advantage of a 117-v filament and a built-in half-wave rectifier. A small filter section is all that is needed to complete the required 90-v plate supply. Complete filtering is unnecessary as the presence of ripple helps the oscillator to lock in.

One or two precautions are necessary in the adjustment of the timer. The chassis must be grounded through a condenser C_7 to one side of the 117-v line. Shielding the neon tube improves the operation. Since there are individual differences in these tubes, the circuit constants of C_6 and R_1 are subject to some variation. In practice, the capacitance of C_6 is varied until, at the frequency desired, there is no "roll" or periodic variation in the vibration of the relay. The lock-in can be checked with a cathode-ray oscilloscope or by viewing the relay armature with a General Radio Strobotac. The vibrating reed of the latter makes a good frequency standard.

If a cumulative drift in the frequency should occur as a result of slow changes in the characteristics of the neon tube, it can be corrected by readjusting the capacitance of C_6.

The timer has been used in the regular sophomore physics laboratory and has been found to give satisfactory service.

[1] Allied Control Co. P. C. 1.

Social Implications of Physics*

G. W. STEWART
The State University of Iowa, Iowa City, Iowa

EVERY natural person gives some thought to civilization after the war—not that one desires to propose exactly what it should be like but that he is eager to have the most intelligent consideration given the problems that will be pressing at that time. For civilization is a great experiment, the greatest we have, and no one can foresee precisely what will result in any new experiments that concern Nature's ways. One of the influences of the war upon physicists is to make them conscious of applied physics as an integral part of their interest. Using the term *physics* in this more comprehensive sense, one can easily recognize that there must be a connection between the recent advances of physics and the structure of our social and political institutions of tomorrow. Physics will prolong life. It will give greater physical comfort to human beings. It will make available more power per capita. It will enable us to hear more, see more, travel farther and increase the possible experiences of the individual in his lifetime. It will increase the contact between nations, thus making tradition and past history of less and less dominating importance in nationalism. Even though the spirit of intense nationalism has increased during the period of industrial development, advances in physics and its applications will have a definite tendency to reduce extreme nationalism and to facilitate the adjustment of human relations. Physics, along with the other sciences, gives confidence in the use of the human mind and in the mind's creativeness. We need this confidence to offset the backward view of those who imagine we are rushing toward destruction.

But there should be one warning to anyone who seeks to help society only through scientific method. Said a distinguished specialist in medicine a few days ago, "I very much regret to see medicine mechanized, to see the soul of the practitioner underemphasized." Everyone, unless he is too much enamored of the application of the scientific method, realizes that the adjustment of human relations does embody art as well as science. Not until physics and chemistry have so expanded in content that they can explain every biological fact in terms of known principles, not until every phase of human relationship can be analyzed into definite measurable scientific terms—and this appears to be a long, an indefinitely long time ahead—can the experts in social science neglect the emphasis upon the art essential in the adjustments in relationships of human beings.

* An abstract of an address given at The State University of Iowa, Oct. 14, 1942.

Subject Matter for a Course in General College Physics

R. F. Paton
University of Illinois, Urbana, Illinois

Along with the developing realization of the serious shortage in people trained in physics and a growing demand on secondary schools, colleges and research institutions to meet this shortage, it would be well for physics teachers at all levels to consider what material to leave out and what to stress. Physicists may as well admit that they are faddists. Even a casual inspection of the textbooks in general college physics which have appeared in the last 20 years will reveal this. One recent book is constructed quite definitely on the scheme that general physics should be taught as a beginning of training for research on the cyclotron. Books published ten years ago had a strong bent toward spectroscopy. In fact, one needs to go back to books which first came out some 40 years ago to find the kind of physics emphasized that is in vigorous demand for early training today—the physics needed as a basis for engineering training.

The following list of topics in physics was obtained by examining a large number of elementary books that are used in pre-training courses for the engineering industry:

Mechanics

Statics	Friction
Center of gravity	Types of motion
Machines	Moment of inertia

Work, power and energy

Properties of Materials

Solids

Elasticity	Flexibility
Shear	Wearability
Compressibility	Resistance to moisture
Rigidity	Tensile strength
Flexure	Creep
Torsion	Extrusion
Crushing stress	Plasticity
Grain size	Fatigue
Hardness	Thermal stress

Liquids and Gases

Viscosity
Gas laws
Laws of flow: of solids in fluids; streamline *versus* turbulent flow

Molecular Physics and Heat

Thermometry: electrical; optical; radiation
Heat flow: conductivity; convection; latent heat transfer; radiation
Thermal equilibrium: distillation; chemical reactions; heat treatments; absorption and adsorption

Vibration and Waves

Mechanical	Optical
Acoustical	Electrical

Electricity

Potential difference, current and resistance	Ammeters
Batteries	Magnets
Heating effect	Electromagnets
Laws of resistance	Lenz law
Electrolysis	Motors
Avogadro law	Generators
Potentiometers	Magnetic circuit
Galvanometers	Inductance
Voltmeters	Capacitance
	Alternating currents

Two serious blind spots are at once evident. One is characteristic of the physicist, whether textbook writer, teacher or research man. It covers the topics listed under *Properties of Materials*—a subject-matter field that has been almost completely neglected by the physicist. Many college and university physics courses for engineers either omit most of these topics entirely or mention them only briefly, and do so admittedly to gain time for the more modern topics, such as spectroscopy, of prime interest to physicists 15 years ago, or, currently, the study of what the nucleus is like.

The other blind spot appears under *Vibrations and Waves*. Here it seems that the engineer is to blame. He has apparently limited his observations too much to the static case—so much so that many engineers still teach inertia only as something to be determined by weighing.

Briefly, it would seem that in the traditional eight or ten hours per week allowed the teacher of physics in training engineers, more emphasis should be placed on the properties of materials and on the mechanics of vibratory motion. Elsewhere in the fields of physics, a reasonably appropriate job apparently is being done. Certainly mechanics is not overemphasized. Some of the more complex features of electric circuits may properly be omitted from a first course. Specialized courses offering intensive training in specific fields should be used to carry on beyond the first ten hours of college work. It is quite possible that the average practicing engineer would think more of his course in physics if it had not omitted so much of the study of properties of materials in order to gain time for the teacher's current hobby.

Reprints of Survey Articles and Committee Reports for Class Use

Reprints of the following articles and reports which have appeared in various issues may be obtained from the Editor, American Journal of Physics, National Research Council, 2101 Constitution Avenue, Washington, D. C. Stamps will be accepted in payment.

D. R. Hamilton, *Molecular beams and nuclear moments*, 60 cts. for 6 copies.
A. L. Hughes, *Aspects of electron scattering*, 50 cts. for 6 copies.
J. C. Hubbard, *Ultrasonics*, 50 cts. for 6 copies.
W. H. Michener, *A brief table of meter-kilogram-second units*, 15 cts. for 6 copies.
R. P. Johnson, *Solid fluorescent materials*, 40 cts. for 6 copies.
M. S. Plesset, *On the classical model of nuclear fission*, 35 cts. for 6 copies.
D. E. Wooldridge, *The separation of isotopes*, 40 cts. for 6 copies.
M. Randall, *Electrolytic cells*, 60 cts. for 6 copies.
P. W. Bridgman, *Society and the intelligent physicist*, 10 cts. per copy.
A.A.P.T. Committee, *Proposal to standardize letter symbols*, 50 cts. for 6 copies.
A.A.P.T. Committee, *Suggested four-year curriculum leading to a major in physics*, 5 cts. per copy.
A.P.S. Committee, *Physics in relation to medicine* (1923), 10 cts. per copy.
A.A.P.T. Committee, *Teaching of physics for premedical students* (1937), 15 cts. for 6 copies.

Abstracts of Contributed Papers—Twelfth Annual Meeting of the American Association of Physics Teachers

TWELVE contributed papers, the titles and abstracts for which appear below, were listed on the program for the twelfth annual meeting of the American Association of Physics Teachers, Columbia University, New York, January 22–23, 1943. A general account of the meeting and of the award of the 1942 Oersted Medal to Professor G. W. Stewart will appear in the next issue.

1. Why rationalized mks units in physics teaching. PAUL F. BARTUNEK, *Rensselaer Polytechnic Institute, Troy, N. Y.*—Despite the great advantages of the mks system of units, which was adopted unanimously by the International Electrotechnical Commission to take effect on January 1, 1940, teachers of physics and engineering with a few exceptions seem to be reluctant to make the change. This reluctance probably results from a failure to realize its numerous advantages as well as from a feeling among those people used to the older systems that the new one would be bothersome to learn. The purpose of this paper was to point out (i) the ease of changing to the mks system, (ii) the advantages of a single consistent system in all fields of physics and engineering and (iii) the saving of the students' mental energy, which, under the older scheme, was wasted in trying to keep straight several different systems. Writers who have made a thorough study of systems of units have in large majority favored the mks system. The writer's own experience and that of teachers elsewhere who have used the system leads him to recommend it without qualifications. The reaction of students is very satisfactory.

2. Undergraduate college origins of American physicists. OSWALD BLACKWOOD, *University of Pittsburgh, Pittsburgh, Pa.*—The number of physicists who have received bachelor's degrees *after 1919* from American colleges and universities *and* who are listed in *American Men of Science* (1938) are: *37*, Massachusetts Institute of Technology; *21*, Wisconsin; *20*, California, California Institute of Technology, Harvard; *19*, Cornell, Indiana; *18*, Chicago; *16*, Michigan; *15*, Oberlin, Texas; *13*, Minnesota; *11*, Columbia, DePauw, Johns Hopkins, Princeton, Reed; *10*, City College (New York), Park, Ripon, Virginia; *9*, Illinois, Kansas, Kentucky, Mississippi, Ohio State, Pennsylvania, Stanford, Washington (St. Louis), Whitman; *8*, Colorado College, Iowa, Pomona, Union (N. Y.), Yale; *7*, Cincinnati, Colorado, Phillips, Rochester; *6*, Amherst, Oklahoma, Pennsylvania State, Pittsburgh, Rutgers, Utah, Wesleyan (Conn.), Wooster; *5*, Brown, California at Los Angeles, Haverford; *4*, Buffalo, Carleton, Clark, Emporia, Georgia, George Washington, Iowa State, Lehigh, Missouri, Morningside, Nebraska Wesleyan, North Carolina, Ohio Wesleyan, Washington (Seattle); *3 to 1*, 177 institutions; *none*, 518 institutions.

The number of these prospective physicists graduated per 1000 *male* liberal arts and pre-engineering students enrolled in 1925–26 are: Reed, 83.5; Park, 47.8; California Institute, 43.8; Ripon, 35.5; Chattanooga, 27.8; Whitman, 26.2; Oberlin, 23.1; Colorado College, 21.6; Haverford, 19.6; Pomona, 17.5; Clark, 17.0; Cornell (Iowa), 17.0; Mississippi, 16.1; Wooster, 14.9; Rochester, 14.9; Nebraska Wesleyan, 14.6; Indiana, 13.5; Depauw, 13.0; Morningside, 12.7; Wesleyan (Conn.), 12.0; Dickinson, 11.8; Mississippi College, 10.7; Amherst, 10.5; Case, 9.85; Massachusetts Institute, 9.59; Miami (Ohio), 9.17; Emporia, 8.96; Carleton, 8.95; North Central, 8.11.

The number of persons who studied undergraduate physics under certain teachers and later received advanced degrees in physics are: R. R. Tileston (Colorado College and Pomona), 54: Wesley Barber (Ripon), 51; R. L. Edwards (Park and Miami), 51; S. R. Williams (Oberlin and Amherst), 47; O. H. Smith (Cornell [Iowa] and Depauw), 42; F. E. Knowles (Phillips), 31; A. A. Knowlton (Reed), 25; F. Palmer (Haverford), 25; D. M. Nelson (Mississippi College), 23; J. C. Jensen (Nebraska Wesleyan), 22; W. L. Kenyon (Mississippi), 21; B. H. Brown (Whitman), 19; R. D. Rusk (North Central and Mount Holyoke), 16; J. W. Hornbeck (Carleton and Kalamazoo), 16.

3. Remarks on teaching concentrated physics courses. F. T. ROGERS, JR., *University of Houston, Houston, Tex.*—Experiments have been conducted on the efficacy of detailed, highly organized notebooks in the teaching of a concentrated radio physics course. The course lasted 12 weeks, 8 hours per day, and covered algebra (Cooke's admirable textbook[1]), elementary electricity (through a.c. circuits by the *j*-operator method), engineering radio (through certain ultra-high frequency applications), and a concurrent laboratory (through the superheterodyne receiver and certain ultra-high frequency experiments). The students had completed their high school educations approximately ten years previously on the average, and were drawn from all parts of the country. The notes were prepared by the instructors, were written on the blackboard, and formed a substantial portion of the regular electricity and radio lectures. The students were asked to utilize the notes as their text, and to use standard textbooks only as references. In all, some 600 students have been observed, in groups of 100; some were given notes and some were not. It was evident to disinterested observers as well as to the instructors that: (i) the notebook students did not learn appreciably more than the others; but (ii) their morale was markedly better than that of the others, thus greatly reducing discipline problems; (iii) one cannot expect such students as these to read standard textbooks rapidly with profit; (iv) from an administrator's point of view, it appears that the relatively strict and vigorous use of notes such as these is one way for an

inexperienced instructor to teach effectively in a high speed, war-time course.

[1] N. M. Cooke, *Mathematics for electricians and radiomen* (McGraw-Hill, 1942).

4. Physics in cartoon and comic strip. ROBERT S. SHAW, *College of the City of New York, New York, N. Y.*—For several years the author has been filling scrapbooks with items, taken from lay newspapers and magazines, having a bearing on physics or the teaching thereof. Many of the items are single cartoons, or one or more frames from a comic strip, in which principles or applications of physics are shown either correctly in exaggerated form or incorrectly in a spectacular manner. The slides shown on this occasion were chosen from the scrapbook on mechanics.

5. Physics in an accelerated program—some observations. BERNARD B. WATSON, *University of Pennsylvania, Philadelphia, Pa.*—As part of the accelerated program at the University of Pennsylvania the full year of general physics was offered in a summer session of 12 weeks. Neither content nor thoroughness of treatment was sacrificed; in fact, there were significent additions of material chosen from the more recent developments in physics. Despite the increased content and speed of presentation of the subject matter, the level of student achievement in the course was at least equal to and probably higher than that obtained previously. Since the size of the class—150 students—would minimize the chance that the group was in any way select, it is concluded that the content of the general physics course can be materially increased without diminishing the degree of success realized in teaching basic physical principles.

6. Dynamic tests for the laboratory. LOUIS R. WEBER, *Colorado State College, Fort Collins, Colo.*—While written lessons and tests that include questions on the laboratory work are customary, the author has always felt that better methods of testing could be developed. On the assumption that sufficient familiarity with and appreciation of equipment and instruments for accurate measurements are necessary, different instrumental setups are arranged in the laboratory with an assignment number and question attached. For example, the assignment sheet attached to a telescope reads: "No. 4. What is the magnification of this instrument?" The better students will think their way to the use of the panes of glass in the laboratory windows to answer this question with the use of the telescope. The poorer students always feel that the available data or equipment are inadequate but are stimulated in their thinking when they realize that this is not the case. Some of the numerous setups used were described. The students are enthusiastic about such a test and seem to be greatly benefited.

7. Some results from a new objective test for engineering and physical science aptitudes. MARSH W. WHITE and CHARLES H. GRIFFIN, *Pennsylvania State College, State College, Pa.*—A new test has been developed to measure engineering and physical science aptitudes of men and women at the secondary school graduate level. It covers mathematics, formulation, physical science comprehension, arithmetic reasoning, verbal comprehension and mechanical comprehension. Intended to appraise aptitudes for work in technical studies and occupations, the test has been validated with a large population of ESMWT students in the extension program of the Pennsylvania State College. Correlations and reliability indices are available. Much of the work of formulating the test was done by C. J. Lapp, State University of Iowa.

8. Two experimental demonstrations of the properties of air flow. G. P. BREWINGTON. *Lawrence Institute of Technology, Highland Park, Mich.*—(i) Fluid flow around objects can be illustrated by the properties of the horizontal flow of water over a slightly inclined sheet of plate glass. The actual flow is made visible by placing several crystals of potassium permanganate near the upper end of the glass. Various two-dimensional models may be placed on the glass, and the flow lines studied by observing the streams which come from the crystals. By observing the small particles which break away from the crystals one can obtain a good idea of the velocity changes about certain portions of the model. If the inclination of the glass and the flow of water are carefully controlled, the flow is nonturbulent. Usually insufficient potassium permanganate dissolves to make the turbulent flow visible. (ii) Models of the Tacoma Narrow Bridge can be made from thin sections of plywood or Masonite and suspended by several long springs. These models, when placed in front of an electric fan, readily show the mode of oscillation that destroyed the bridge. A number of such cases of instability are known and will, no doubt, soon be a part of most physics lecture demonstrations.

9. Demonstration of particle motion in an inverse square field of force. C. L. HENSHAW, *Colgate University, Hamilton, N. Y.*—Students of elementary physics find it difficult to appreciate the kind of motion described by Kepler's three laws and followed by planets or satellites in a solar system. A simply constructed model serves to demonstrate the main features of this motion. A ball is allowed to roll on a wooden "bowl" the surface of which is part of an equilateral hyperbola rotated about one asymptote. The potential energy of a ball on this surface is inversely proportional to the distance from the axis of rotation; hence there is a central force that varies inversely with the square of the distance from the axis. The variation of linear speed of the ball according to Kepler's second law of constant areal velocity is easily shown when the orbit has moderate ellipticity. This is also brought out with stroboscopic photographs. Two effects prevent this model from being a perfect demonstration of Keplerian motion: friction causes the ball to drop into the center after a few revolutions; and the rotational kinetic energy of the ball, as distinguished from its orbital kinetic energy, causes the orbits to precess. Effects of varying the size and density of the balls were discussed and demonstrated.

10. New type "collisions" apparatus. H. K. SCHILLING, *Pennsylvania State College, State College, Pa.*—To demon-

strate the phenomena of collisions of balls of equal mass recourse is usually had either to balls that are supported by bifilar pendular suspensions or to balls that roll along a track of some sort. The present apparatus consists of two horizontal, parallel, tightly stretched piano wires that support a row of pool balls through each of which have been drilled two holes off center, the wires being threaded through these holes. This apparatus does not get out of adjustment as easily as the first of the more common types. Central collision is insured. Complications due to rotation, inherent in the second older type, are eliminated. Experiments can be performed that otherwise would be extremely difficult or impossible.

11. Waterproofing and wetting demonstrations. ERIC M. ROGERS, *Princeton University, Princeton, N. J.*—(i) To show the efficacy of "wetting agents," a new, unlaundered, cheap dishcloth is dipped in water colored with dye and then in the same colored water with a little wetting agent added. (ii) To show the part played by angle of contact in waterproofing, a large model is used in a projection lantern. The cloth fibers are represented by $\frac{3}{8}$-in. wooden rods in a transparent plastic box containing a thick layer of olive oil floating on water. One liquid represents air, the other water. When the liquid interface is pushed up between the rods, by adding water, the rods behave as "waterproof" or not according to their treatment, *or* according to which liquid is chosen to represent water. Two boxes may be used, one with oiled rods, the other with rods treated with soapy water; or one box may be used and the liquid interface moved down for the second case, oil and water then interchanging roles and a prism being employed to invert the picture.

12. Use of a theory in elementary teaching. ERIC M. ROGERS, *Princeton University, Princeton, N. J.*—The words *theory* and *hypothesis* suffer—quite apart from looseness of definition—because of the failure of students to appreciate their *use*. An excellent illustration of their use is provided by the molecular theory of magnetism. For example, without the theory, a "steel ring that is magnetized without showing any poles" sounds absurd, but with it the statement makes sense.

Annual Report of the Treasurer, American Association of Physics Teachers

Balance brought forward from Dec. 15, 1941		$ 4,426.75
CASH RECEIVED		
Dues received for 1942[1]	$4,505.00	
Dues received for 1941	20.00	
Dues received for 1943	147.50	
Grant	1,500.00	
Royalties, *Demonstration Experiments in Physics*	187.87	
Membership fee for A.C.E., paid by American Institute of Physics	100.00	
Donations	25.45	
Total deposited, 12/15/41 to 12/15/42		6,485.82
Total cash available		$10,912.57
DISBURSEMENTS		
Postage and supplies	$ 197.47	
Printing	29.39	
Secretary's office expense	402.49	
Membership chairman's office expense	161.70	
Constituent Membership in A.C.E.	100.00	
Stenographer, editor's office	609.00	
Editor's traveling expense	16.89	
Payments to American Institute of Physics	2,147.55	
Traveling expense, A.C.E. representatives	56.46	
Discount on Canadian and Hawaiian checks	3.77	
Journal survey articles	27.00	
Money advanced on *Demonstration Experiments in Physics*	147.99	
Oersted medals and cases (3)	45.15	
Regional Meeting, Dallas, Tex.	24.10	
Pennsylvania State College Meeting	15.25	
Total disbursed		3,984.21
Balance on hand Dec. 15, 1942[2]		$ 6,928.36

PAUL E. KLOPSTEG, *Treasurer*

I have audited the books of account and records of Dr. Paul E. Klopsteg, Treasurer of the American Association of Physics Teachers, for the year ending December 15, 1942, and hereby certify that the foregoing statement of receipts and disbursements correctly reflects the information contained in the books of account. Receipts during the year were satisfactorily reconciled with deposits as shown on the bank statements, and all disbursements have been satisfactorily supported by vouchers or other documentary evidence.

Chicago, Illinois,
December 21, 1942.

WILLIAM J. LUBY
Certified Public Accountant

[1] On December 15, 1942, there were 953 members in good standing.
[2] A balance of approximately $500 is due the American Institute of Physics for the publication of the journal in 1942.

RECENT PUBLICATIONS AND TEACHING AIDS

ELEMENTARY PHYSICS

A laboratory manual of experiments in physics. Ed. 5. L. R. INGERSOLL, Professor of Physics, University of Wisconsin and M. J. MARTIN, Professor of Physics, Milwaukee Extension Center, University of Wisconsin. 353 p., 139 fig., 14×21 cm. *McGraw-Hill*, $2.50. Two new experiments have been added to the 84 that appeared in the previous edition [Am. J. Phys. **5**, 42 (1937)]. Several of the original experiments have been extended and others have been revised, but in all cases the older methods have been retained as alternative procedures. Greater emphasis has been placed on graphical methods, particularly on the use of logarithmic and semilogarithmic graphs.

Mechanical physics. HERBERT DINGLE, Professor of Natural Philosophy, Imperial College of Science and Technology, London. 255 p., 61 fig., 13×19 cm. *Ronald Press Co.*, $2.25. *Aeroscience Manuals*, of which this is the first volume, is a series intended to cover all the sciences underlying aeronautics, presenting them in a way consonant with the purposes of the manuals. The present volume, like the next to follow, which will be called *Subatomic Physics*, is essentially a textbook of physics. The treatment is clear and interesting; and it is relatively simple, although some knowledge of elementary mechanics is required of the reader and calculus is employed in a few sections which, however, can be omitted without serious loss. Taking the position that with the advent of modern physics the traditional way of dividing elementary physics into five or six branches has been rendered obsolete, PROFESSOR DINGLE prefers instead to distinguish those departments of the science in which the atom or molecule can still be treated as an elementary particle from those in which the structure of the atom is fundamental. The effect of this classification on the traditional one is broadly to place properties of matter—that is, the behavior of matter under the influence of external and internal forces—heat, wave motion and sound under "mechanical physics," and light, magnetism and electricity under subatomic physics. Such important topics as radioactivity, x-rays and photoelectricity enter naturally into the new classification, whereas in the older division they had no place.

ADVANCED PHYSICS

Electrical counting. W. B. LEWIS, Cavendish Laboratory. 148 p., 68 fig., 13×21 cm. *Cambridge University Press* and *Macmillan*, $2.50. This monograph on electrical counting, with special reference to the counting of alpha- and beta-particles, should be of interest not only to workers in nuclear physics, where the technic has been developed as an essential aid, but to many in other fields who have occasion to use tube circuits. The main topics discussed are ionization by single particles, counting ionization chambers, limitations of amplifiers, design of amplifiers, oscillograph recording, feedback and stabilizers, nonlinear applications of tubes, recording counters, Geiger-Müller tube counters, statistics of random distributions, coincidence counting and energy determinations from range measurements.

Scattering of light and the Raman effect. S. BHAGAVANTAM, Professor of Physics, Andhra University. 343 p., 39 fig., 66 tables, 13×21 cm. *Chemical Publishing Co.*, $4.75. This is the first American edition of a text- and reference book which has grown out of a course of lectures given by the author at Andhra University during the past five years. As PROFESSOR RAMAN points out in a Foreword, the book brings together the scattered literature on the Raman effect and presents a connected account of the experimental facts and underlying theories; hence it should serve to stimulate further work in a field which, though extensively cultivated, has not yet yielded all the results of which it is capable, especially in the study of the solid state. The treatment is confined mainly to the physical aspects of the subject, although three of the 18 chapters deal with the Raman effect in relation to inorganic, physical and organic chemistry.

The theory of the photographic process. C. E. KENNETH MEES, Eastman Kodak Company. 1134 p., 406 fig., 89 tables, 16×24 cm. *Macmillan*, $12. The purpose of this authoritative and elaborate work is to provide a general survey of photographic theory that will serve as a guide to the literature as well as a summary of its conclusions. The literature of the field covers a period of some 50 years and is scattered through 150 periodicals in several languages; but in the arduous task of digesting and interpreting it the author has had the able assistance of numerous other specialists in the Kodak Research Laboratories, who have either written or aided in the revision of various chapters. The 25 chapters, each containing an extensive bibliography, are grouped into six main sections: (i) the photographic material, (ii) the action of light, (iii) the development and the after processes, (iv) sensitometry, (v) photographic physics, which deals with the theory of tone reproduction, the physics of the developed image and the photographic aspects of sound recording, and (vi) optical sensitizing.

PAMPHLETS, MONOGRAPHS AND POSTERS

Heat transfer through metallic walls. 16 p. *International Nickel Co.* (67 Wall St., New York), gratis. Information on over-all heat transfer rates, the factors influencing heat transfer through metallic walls, and the thermal conductivities of metals and alloys.

Requirements for 16-mm motion picture projectors. R. E. STEPHENS. Circular C437. *Superintendent of Documents* (Washington, D. C.), 10 cts. This National Bureau of Standards circular describes in detail the requirements for a satisfactory projector and gives procedures for testing its important characteristics—light output, image definition

and steadiness, freedom from flicker, durability, wear on film and simplicity of operation.

Static electricity. F. B. Silsbee. National Bureau of Standards Circular C438. *Superintendent of Documents*, 10 cts. Methods used for mitigating industrial fire and explosive hazards due to static electricity.

Entropy. K. K. Darrow. 24 p. Monograph B-1347, *Bell Telephone Laboratories*, gratis. An enlightening discussion of *entropy* and of "the theories which profess to give its absolute value."

The future of transoceanic telephony. O. E. Buckley. 19 p. Monograph B-1346, *Bell Telephone Laboratories*, gratis. The 33rd Kelvin Lecture of the Institution of Electrical Engineers.

Thermostat setting and economy in house heating. LC694. *National Bureau of Standards*, gratis.

Climate and man—the 1941 yearbook of agriculture. 1248 p. *Superintendent of Documents;* also may be obtained gratis by writing to one's congressman. More than half of this book deals with the scientific approach to weather and climate and with climatic data of definite interest to physicists who are teaching meteorology. Four of the eight members of the Yearbook committee were drawn from the U. S. Weather Bureau.

General Electric Company educational publications. *General Electric Co.* (Dept. 318–6, Schenectady, N. Y.), gratis:

General Electric motion pictures, GES-402. Catalog of educational films.

Television, GES-2405. How television works and something of its history.

The invisible world and other stories, GES-2962. Adventures of nine scientists in electricity.

The story of lightning, GEB-124. How lightning is studied in order to help improve electric service.

The story of Steinmetz, GEB-104. A brief biography.

Photo News Service. A series of posters, issued twice monthly throughout the school year, that illustrate and describe new research developments. An attractive wooden frame will be furnished with the first poster.

Useful data for electrical men, GEA-3798. Contains some of the fundamental data for electrical engineering.

New England Section of the American Physical Society

THE twentieth regular meeting of the New England Section of the American Physical Society was held at Trinity College, Hartford, Connecticut, on October 24, 1942. At least 45 members were in attendance. The invited papers were as follows:

The training of meteorologists for the armed services. H. G. Houghton, *Massachusetts Institute of Technology*.
Physics at Trinity College. A. P. R. Wadlund, *Trinity College*.
Intra- and extra-curricular war courses at Smith College. Nora M. Mohler, *Smith College*.
Applications of high voltage electrons in nuclear research. Herman Feshbach, *Massachusetts Institute of Technology*.

Eight papers were contributed, of which two pertain to instruction, as follows:

Experiments with a condenser. Rogers D. Rusk, *Mount Holyoke College*.—A digest of this paper appears under "Notes and Discussion" in this issue.

Common misconceptions among first-year physics students. Henry A. Perkins, *Trinity College*.—An outline was given of a proposed, popular series of lectures for school physics teachers, dealing with certain persistent errors in the thinking of first-year college students that should be corrected. Several specific misconceptions and methods found useful in eradicating them were discussed.

The abstracts for the remaining six papers appear in *The Physical Review* **62**, 558 (1942).

At the business meeting the following officers were elected for the current year: Gladys A. Anslow, *Chairman;* A. P. R. Wadlund, *Vice Chairman;* Mildred Allen, *Secretary-Treasurer;* C. E. Bennett and W. W. Stifler, *Program Committee*.

Mildred Allen, *Secretary-Treasurer*

Errata. In the article by R. B. Lindsay, "Galileo Galilei, 1564–1642, and the motion of falling bodies," Am. J. Phys. **10**, 285 (Dec. 1942), interchange the legends for the plates on pages 287 and 290, and replace "Galti" by "Gatti."

DIGEST OF PERIODICAL LITERATURE

A Model Illustrating Intercrystalline Boundaries and Plastic Flow in Metals

A two-dimensional model that illustrates the plastic flow of a metal is easy to set up and makes a good lecture-demonstration. A raft of small bubbles is formed on the surface of a soap solution by blowing air at constant pressure through a fine orifice beneath the surface. The very uniform bubbles so produced "crystallize" regularly. By attaching opposite sides of the raft to springs which lie on the surface, the raft can be sheared uniformly, the slip process observed and a stress-strain curve plotted. The model illustrates the nature of intercrystalline boundaries and the complex series of slips caused by crushing the raft. The original article should be consulted for details.—L. BRAGG, *J. Sci. Inst.* **19**, 148–150 (1942). D. R.

Photographic Transparencies for the Museum

Portraits of eminent scientists or other similar material are copied with the camera from halftone illustrations in books. The negatives are then printed by projection on Defender Company Adlux paper, which is composed of a heavy celluloid composition coated on both sides with the Velour Black emulsion. Printing and developing is precisely the same as with ordinary enlarging paper. The completed, translucent picture is mounted on translucent mimeograph paper and attached to the glass pane of a window. A protecting pane of glass is then permanently mounted over each picture. The project can be carried out by students having a limited knowledge of photographic technic at a total cost of about four dollars for three dozen pictures.—C. TANZER, *Sch. Sci. and Math.* **42**, 758–759 (1942). D. R.

A Mathematical Card Game

Prepare a deck of 50 or more rectangular cards cut from cardboard. Place a number from 0 to 7 on each card, expressing it in some symbolic manner. Thus, for *0* write $1+\cos 180°$, $\log 1$, $\cos \frac{1}{2}\pi$, $0-0$, 6^0-1, etc.; for *1* write i^4, $\cos 0°$, $\log_e e$, $1+\cos 180°$, $\tan 225°$, etc.; for *2* write $d(2x)/dx$, $4^{\frac{1}{2}}$, $\cos^2 45°$, ${}_2C_1$, $(12)^{\frac{1}{2}}/\sqrt{3}$, $\sec \pi/3$, $2\tan^2 225°$, etc.; for *3* write $(81)^{\frac{1}{4}}$, $3\sin 90°$, $(7+\sqrt{4})^{\frac{1}{2}}$, $3(5)^0$, $\cot^2 30°$, $6/(8)^{\frac{1}{3}}$, etc.

From two to eight players may participate. All the cards are distributed, one at a time. The dealer starts the game by placing a card face down on the table and calling it "zero." The player to his left places a card face down in front of him and calls "one"; the next player does likewise and calls "two," and so on around the table. If at any time a person doubts that the number put down was the one declared, he challenges the player, who must then expose the card played. If it was the card declared, the challenger must take all the cards the player has on the table in front of him; if it was not, the player must take all of the cards the challenger has before him. When all cards in the hand have been played, the player picks up all of his cards remaining before him on the table and plays them again. After counting to seven, the next player may lay down any number he wishes but the players to his left must then lay down the next consecutive numbers until 7 is reached. The object of the game is to see who can get out of cards first.—I. PRICE, *Am. Math. Mo.* **49**, 117 (1942). D. R.

Foreign Scientists in America

In 1794 Joseph Priestley came to this country, and was made welcome by the American Philosophical Society, which had elected him to membership in 1785. It is in the same spirit that various institutions have welcomed those who have been driven from Europe during the past ten years. There are many well-known forerunners of the great migration that began in 1933. From the beginning of that year to the middle of 1942 at least 130 mathematicians and physicists have come to America and, through the efforts of a number of agencies, have been introduced to positions in which their talents and training can be used to advantage for the enrichment of science.—A. DRESDEN, *Am. Math. Mo.* **49**, 415–429 (1942). J. D. E.

Constant of Gravitation

The Newtonian constant of gravitation has again been determined by the same general method as was previously employed by the author [Heyl, *J. Research Nat. Bur. Stand.* **5**, 1243 (1930)]; namely, by observing the change in period of a torsion pendulum resulting from the presence or absence of large attracting masses in its neighborhood. Of various suggested improvements in the apparatus, several were tried and two were adopted. These two were the use of photographic recording of the period in place of visual observations, and a change in the position of the large attracting masses which greatly simplified the length measurements. Two different tungsten filaments were used as a suspension for the pendulum, one hard drawn and one specially annealed and kept straight during the drawing and subsequent handling. The results with the hard-drawn filament turned out to be the more precise. The only advantage of the annealed filament was that it required less aging after installation—a factor of importance only where time is an object, as in geophysical prospecting.

The final result obtained was

$$G=(6.673\pm0.003)\times10^{-8}\ \mathrm{cm^3\ gm^{-1}\ sec^{-2}}.$$

Comparison with the 1930 result of $(6.670\pm0.005)\times10^{-8}$ shows that the increase in precision is hardly appreciable and hence that the limiting point of diminishing returns has been reached with this form of apparatus.—P. R. HEYL, *J. Research Nat. Bur. Stand.* **29**, 1–31 (July, 1942). D. R.

Effective Presentation of Papers at Meetings

In giving papers at society meetings the greatest fault of scientists lies in their attempt to present material orally that was prepared primarily for publication in a technical journal. Lack of skill in oral presentation is a handicap, but one cannot chide the research scientist too much on this score; he has other things to do besides taking elocution lessons or rehearsing his address with the intensity of a radio program director.

What the scientist can do, however, is to rise above the laziness whereby he tries to kill two birds with one stone. Thus he might well come to the meeting armed with two manuscripts. One would be his technical paper intended for publication—the kind of report which he now reads to a bored audience; its sole use at the meeting would be for those few individuals who come to him after the talk for more technical details. The other manuscript would be his oral presentation. It would tell the story of his work in a simple, summary fashion, relatively free from technical terminology and with the emphasis on what has been accomplished, on *what the work means* rather than on the specific details of how it was done. In preparing an effective oral presentation the scientist might well adopt something of the technic of the professional science writer, who places the question, "What does it mean?" at the top of his list of requirements.

Scientists have rightly been taken to task for "reading" their papers in a fumbling halting fashion. However, most scientists, if they have prepared their statements in oral English, in contrast to written and scientific English, will find it possible to *read* their papers and still make them effective and interesting.—R. D. Potter, *Science* **95**, 503–504 (1942). D. R.

A Grating Spectrograph

The "Technal" mounting is the most recent of the minimum astigmatism mountings for a concave grating. It is made commercially by Adam Hilger, Ltd., but they do not claim its invention. Because of its simplicity, both in principle and in construction, a workable instrument can be made in almost any shop. It is suitable for student use in lieu of more delicate and expensive apparatus.

The slit A and the grating B (Fig. 1) are fixed to the ends of two rods, each of length one-half the radius of curvature of the grating. The other ends of the rods are joined by a pivot C. The point A is pivoted on the bed of the instrument, and the point B is allowed to slide on the bed as the point C is moved toward or away from the bed. It is evident that A and B will always be on the Rowland circle of the grating, of which C is the center. The joint C is connected by a short toggle to one end of a lever, pivoted on the bed between A and B, so that the motion of C is controlled by the motion of the other end of the lever. This end moves over an arc of a circle, on which a rough scale of wavelengths is marked by trial after the instrument has been set up and adjusted. The lengths of the two arms of the lever are such that there is a slight mechanical advantage and hence greater precision in the motion of C.

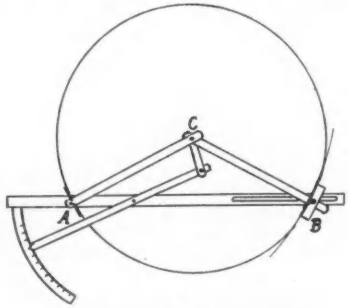

Fig. 1. Diagram of the spectrograph.

The "plate" is curved to conform to the curvature of the Rowland circle and is mounted with one end next to the slit. A replica grating with a radius of curvature of 1 m is satisfactory, but it is obviously impossible to bend a glass plate into an arc of half this radius. Consequently, 35-mm motion-picture film is used, or pieces of cut film can be trimmed to the desired size. A simple film holder can be made to hold the film with the proper curvature. In order to limit the length of the spectral lines on the film, the holder is provided with a slit, preferably of variable width, which is at right angles to the slit A. The whole instrument is mounted in a light-tight housing, which should have a door near the grating end for the purpose of making such adjustments as may be necessary.

For comparison of two spectra—for example, in qualitative analysis—a Hartmann diaphragm is convenient. It may be made of two small brass hinges screwed to a block of wood so that when the two hinges are open flat their movable leaves do not quite touch. Behind the slit so formed is a hole bored in the wood. Thus when two exposures are made with one hinge open at a time, the lines of the spectra will overlap slightly, which greatly facilitates comparison.—W. S. von Arx, *J. Chem. Ed.* **19**, 407–410 (1942). J. D. E.

The Making of a Physicist

The good physicist, like the poet, is born and not made. Neither can be produced, on demand, by any system of training. If, following Sir Lawrence Bragg, we define a good physicist as "a man capable of independent thought, with a flair for his subject," then about one good physicist is bred per year per million inhabitants, an estimate that agrees fairly closely with the records in both Great Britain and the United States. It is unlikely that the grand total of available physicists coming within the scope of the foregoing definition can be materially increased; yet the number falls much below present requirements, and well below the requirements of a post-war society in which science will play its proper part.

Fortunately, the situation is less desperate than it seems. The standard set by Sir Lawrence's definition is a high one—few, if any, other professions make such rigorous demands of their membership—and many routine but important

tasks for which physicists are required can be adequately performed by people less gifted. There will be posts for many such people in post-war industry. With these new recruits available, the always strictly limited number of men with a real flair for research can be assigned to work which they alone can do.

The distinction between education and training is of particular importance when dealing with the making of a research physicist. Though his discoveries sometimes lead to considerable advances in engineering, the research physicist is not a kind of super-engineer; in fact, industrialists who try to employ him on engineering work usually find him distinctly disappointing. His real affinity is with the creative artists, and his value to the community lies in the spark of originality that he brings with him into the world. To assist such a student to develop his full stature as a physicist is our first and most urgent task. Training for a more specific task should follow, not accompany, this process of education. Since the distinction between the "good physicist" and what we may call the routine physicist is one of degree rather than kind, the same process presumably should also be applied to the latter, up to the limits of his capacity.

Education at its best is a very personal matter. The student gains more from contact with the minds and personalities of his professors than from formal instruction. That is one reason why the university with its happy blending of teaching and research embodied in the same individual affords such an excellent cultural medium for the embryo physicist. However, one grave error has undoubtedly developed. In an attempt to keep pace with the rapid growth of the science, far too heavy a load has been placed upon the shoulders of the "honors" physics student. He does not have the leisure in which to grow up. To quote Sir Lawrence Bragg again, "He has not learnt to mix with other people, and form one of a team, to take responsibility, to trust his own judgment, and to have initiative. . . . The industrialist compares him unfavorably with boys who have worked their way up, become men of the world."

Although this picture is a little overcharged, that there is much substance in it cannot be doubted. The suggestion that the problem could be solved by interpolating a six month's apprenticeship to industry for all honor students between their leaving school and entering university is of doubtful efficacy. Apart from the fact that a definite break in the student's career at this stage might be undesirable in itself, there is the risk that this preliminary apprenticeship might lead the student to regard his subsequent studies as a training for industrial service rather than as an education in physics; and to be impatient (anyone who has taught physics to medical or engineering students will know the symptoms) of matters of no obvious practical importance. But it is precisely because the physicist, for the shear love of the subject, has studied many matters of no obvious practical importance that he is able to make his unique contribution to industry. The trouble actually lies not in the university environment, but in the fact that the physics student has been largely isolated from this environment because of the pressure of work. The remedy is to lighten the load and so give him the opportunity to participate in the nonacademic but formative activities that are such a valuable part of university life.

The system whereby the young graduate is trained by allowing him to spend a year or two in research in the university has grown up fortuitously, but its value has not been seriously challenged by the industrialist. It would probably be difficult to devise anything better. However, both the student and the research director should keep clearly in mind that the object is to produce a research physicist and not a series of publishable papers. The neophyte should be given a problem that will test his powers, and he should be allowed considerable latitude in handling it. The freedom to make one's own mistakes plays a valuable part in the training process. The temptation to use the student as an observer in other people's researches should be firmly resisted, and the department should be satisfied to be judged primarily by the quality of its graduates rather than by the quantity of original papers it turns out. In this connection the methods of J. J. Thomson, the greatest trainer of research physicists the world has yet seen, are worth close study.

While the routine physicist usually settles down quite readily in industry, the research physicist too often both experiences and creates a certain irritation. Eager to prove his worth and give his best, he finds himself enmeshed in a system of regulations which appear to him to have been specially designed to hinder him in his work. Often he has to do things that seem to him of negligible importance. There is need for adjustments on both sides if physics is to make its maximum contribution to the welfare of society. Not only must the physicist learn to fit himself for industrial conditions—industry must also learn to adjust its conditions to the physicist. What is needed is a better understanding of the conditions which are essential to the *creative artist* if he is to give the best of which he is capable. To make the necessary adjustments in organization may not be easy; it requires courage and vision, qualities in which the great industrialist should not be lacking. Progress has been made, particularly in the United States.

Thus the problem of the best utilization of our limited scientific capital involves more than the provision of the best methods of educating and training the student; the conditions under which his special gifts can find their amplest outlet must simultaneously come under review. It is only as the two aspects of the problem are studied in conjunction that the right solution will be attained.—Editorial, *Nature* **150**, 245–247 (1942). D. R.

Check List of Periodical Literature

The mathematical expression and interpretation of scientific measurements. W. W. Razim, *J. Chem. Ed.* **19**, 411–414 (1942). A condensation of the theory of errors and related topics, avoiding mathematical derivations, prepared originally for distribution in an industrial laboratory.

The physicist in industry. J. W. Buckley, *J. Sci. Inst.* **19**, 145–148 (1942). Types of industrial problems, comparison

of industrial and academic work, and similar topics are covered.

Edmond Halley, 1656–1742. N. T. Bobrovnikoff, *Sci. Mo.* **55**, 439–446 (1942). "He dazzled his contemporaries by his remarkable erudition, yet he was great enough to subordinate his own considerable talent to the transcendent genius of Newton."

Some early American physicists. H. C. Richards, *Proc. Am. Phil. Soc.* **86**, 22–28 (1942). On Franklin and his contemporaries in the Philadelphia area.

Mechanism of metallic friction. F. P. Bowden and D. Tabor, *Nature* **150**, 197–199 (1942).

Teaching of color in schools. Anonymous, *Nature* **150**, 422–423 (1942). Although the subject of color can occupy only a small corner in school and college curriculums, color phenomena are so intimately woven into the pattern of human experience that what is taught is worthy of the best possible presentation.

A rheological chart. L. Bilmes, *Nature* **150**, 432–433 (1942). A graphical representation of the interrelation of rheological properties.

"He teaches mostly freshmen." G. Wakeham, *Sch. and Soc.* **56**, 409 (1942). College teaching, which has been and is being savagely criticized, particularly at the freshman level, will not be notably improved until administrators are willing to encourage and promote instructors who have demonstrated superior teaching ability, even if they teach "mostly freshmen."

The electron microscope. E. F. Burton, *Am. Scholar* 11, 403–415 (1942). A popular article.

The mechanical properties of glass. F. W. Preston, *J. App. Phys.* **13**, 623–634 (1942).

Blaise Pascal, 1623–1662—tercentenary of the calculating machine. S. Chapman, *Nature* **150**, 508–509 (1942). A brief biography of this mathematician, physicist, inventor and great literary artist, "whose intellectual passion for truth made him utterly dissatisfied without a spiritual explanation of human life." "Newton . . . was a greater man of science than Pascal, but I judge Pascal to be the greater man."

The structure of atomic nuclei. R. D. Evans, *J. Chem. Ed.* **19**, 549–550 (1942). A brief survey, with a chart showing the known stable and naturally radioactive nuclei.

David William Cornelius, 1885–1942

THE many friends and professional acquaintances of David William Cornelius were shocked and grieved to learn of his death on June 2, 1942, at Vincennes, Indiana. It was known that he had been in ill health for several years; but few outside of his family understood the seriousness of the incurable disease, cerebral arteriosclerosis, which finally caused his death. In an endeavor to regain his former vigorous health Doctor Cornelius had assumed part-time duties in 1939, had been granted a leave in 1940, and in 1941 was given emeritus status by the University of Chattanooga.

Doctor Cornelius was born at Linton, Indiana, on April 28, 1885. In 1906 he received his A.B. degree from DePauw University. After graduate study at the University of California and the University of Illinois, he was granted the doctorate by the latter institution in 1912. His research interests were in the fields of photoelectricity, high resistance and instructional methods in physics. He held positions as assistant in physics at DePauw, California and Purdue, professor of physics and engineering at Ottawa (Kansas), assistant professor of physics and astronomy at Kansas University, instructor in physics at the University of Missouri, professor of physics at Alma College and—since 1920—as head of the physics department at the University of Chattanooga.

He was an early and enthusiastic member of the American Association of Physics Teachers, serving on its council and interesting many new members in the Association. In the Tennessee Academy of Science he was president in 1932 and a member of its executive committee. Sigma Pi Sigma, physics honor society, elected him to its executive council and vice-presidency. He was a regular and alert attendant at the various meetings of the scientific societies of which he was a member.

The record of Doctor Cornelius as a physics teacher is a long and enviable one. His zeal and skill in developing physics students is reflected in the large number of his "majors" who pursued graduate work and made excellent records in the leading universities. He labored earnestly to build up his department and had high standards of scholarship. In keeping abreast of his field, Doctor Cornelius cultivated in his students the spirit and methods of original research. His effective work will be missed in these difficult times.

MARSH W. WHITE